MECHANICAL PROPERTIES AS A BASE FOR HAPTIC SENSING OF VIRTUAL FABRICS

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ABSTRACT
The main goal of the European HAPTEX project (HAPtic sensing of virtual TEXtiles) is to develop and validate a novel global method of creating multimodal interacting environments, including haptic, tactile and visual rendering. The example chosen for this development work is “Multimodal perception of textiles in the virtual environment”. The aim of the project is to create a virtual textile that a person can perceive, touch and manipulate. The multimodal interaction consists of visual representation of the cloth simulation and haptic and tactile interface which are integrated and the user is allowed to sense and identify the typical properties of different kinds of fabrics.

In order to present different types of textiles in the virtual system, data of the mechanical properties of the fabrics is required. The KES-F (Kawabata) system offers a sensitive measurement method for the determination of bending, compression, tensile, shear, surface roughness and friction properties. Some modifications to the standard tests were required, in order to provide appropriate input for the simulation of the fabrics. All properties are needed for the haptic/tactile rendering, whereas the tensile, shear and bending properties are used for the visual rendering.

Altogether 54 different fabrics were chosen for the tests. The first set of 20 fabrics were very different in their structure (raw materials, construction, weight and thickness), in order to define the range of variability. The second set was focused on men’s woven suit fabrics and elastic knitted fabrics. And the third set was focused on warp knitted fabrics for car seat covers.

The measured mechanical properties will be validated with subjective assessments in the validation phase of the project.

1 INTRODUCTION
Textiles can be considered one of the most challenging materials in the world when predicting their behaviour due to their versatile combination of properties, structures, raw materials and production techniques. The virtual world is now in front of a big challenge when offering new ways for perceiving, touching and manipulating of textiles. The multimodal perception of textiles in the virtual environment consists of not only the visual part but also the haptic and tactile elements. The aim is to develop and integrate the visual representation of the cloth simulation and haptic and tactile interface to allow the user to sense and identify the typical properties of different kinds of fabrics.

When we touch and manipulate a real fabric with our hand we get a very subjective idea of the hand properties of the material. In addition to the material itself it is affected as well e.g. by our own preferences and likings, state of our mind, wetness and warmness of our hand and the conditions of the environment. To eliminate the delicate subjective variables the hand properties can be measured objectively using specially developed measuring equipment which are based on a selection of physical properties that best describe the typical hand properties of a fabric. The most commonly known methods for these objective hand measurements are the Kawabata KES-F system developed by the Japanese professor Sueo Kawabata and his working group, originally for woollen men`s suit fabrics, and the FAST system developed by the Australian research organization CSIRO.

The Kawabata KES-F system has certain advantages. It is known as the most sensitive measuring method which produces a range of different parameters and the recorded data and graphs. Therefore it was chosen to give real fabric measurement data for the visual simulation and for haptic and tactile rendering. This is also a new application area for KES-F measurement results.

2 MEASURING METHODS

2.1 KES-F Kawabata system

The characteristic values in KES-F system (table 1) are calculated from the recorded data measured by each tester. The testers measure bending, tensile, shear, compression, surface roughness and surface friction properties of the materials. Determinations are made in warp and weft directions and for surface properties on face and back sides of the fabrics. According to Kawabata [1] bending, tensile, shear and compression are mechanical properties and surface properties and weight and thickness are considered physical properties relating with mechanical properties indirectly.

Table 1. The characteristic values for KES-F properties [1].

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	Shear stiffness	gf/cm·°
	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	Geometrical roughness	µm
Weight	W	Weight/unit area	mg/cm^2
Thickness	T	Thickness at 0.5 gf/cm^2	mm

2.2 Step-tensile

The KES-F data of the tensile behaviour is not sufficient for the visual rendering, where additional information about the viscoelastic damping behaviour of the fabrics is needed. A step-tensile was developed, in which the elongation properties were examined using Testometric M 500 Tensile tester to be able to use different forces and to see the effect of several consecutive extension-relaxation cycles. Each test piece was stretched into five different force cycle steps 10N-20N-30N-40N-50N and it was immediately returned to the starting position after reaching the desired force value. Before next tension the test piece was kept for 120 seconds in a relaxed state. The elongation values were recorded both in warp and weft directions. Other applied test parameters were: 10 mm/min test speed, 100 mm gauge length, 50 mm wide test piece and no pretension.

3 TEST MATERIALS

Three different sets of test materials were chosen for the measurements, 54 fabrics altogether. The first set (32 samples) consisted of a very versatile range of different fabrics to get a very wide range of results. There were woven, knitted and nonwoven fabrics of different densities and weights made from natural fibres, man-made fibres and synthetic fibres and their blends mainly for garments and for furnishing. The weight and thickness was determined for each sample. The sample specifications of the 1st set of fabrics are presented in tables 2a and 2b.

Table 2a. Specification of selected samples of the 1st set of fabrics. (to be continued)

Sample Description	Fibre content	Structure	Weight g/m^2	Thickness mm
1. Denim	100% CO	twill	380	1.60
2. Shirt cotton	100% CO	combined twill	120	0.61
3. Cord	100% CO	velveteen	330	1.76
4. Linen	100% LI	plain weave	250	1.09
5. Gabardine	100% WO	twill	175	0.55
6. Crepe	100% WO	plain weave	145	0.93
7. Silk	100% SE	plain weave	15	0.10
8. Natural silk (bourette)	100% SE	plain weave	150	0.80
9. Wild silk (dupion)	100% SE	plain weave	80	0.44
10. Jute	100% JU	plain weave	300	1.44
11. Flannel	80% WO 20% PES	twill	290	1.53
12. Denim	62% PES 35% CO 3% EL	twill	275	1.13
13. Plaid	35% PES 35% AF 30% WO	twill	270	1.14
14. Tweed	66% AF 14% WO 10% PES 10% CMD	combined twill	270	3.90
15. Velvet	92% CO 8% CMD	velvet	300	1.88
16. Lurex knit	70% PES 30% PA	held stitch knit	215	2.94
17. Crepe-jersey	85% PES 15% EL	rib knit	135	0.73
18. Woven motorcyclist wear fabric, coated	72% PA 28% PU	plain weave	90	0.39

Table 2b. (continuation) Specification of selected samples of the 1st set of fabrics.

Sample Description	Fibre content	Structure	Weight g/m^2	Thickness mm
19. Woven easy care fabric	65% PES 35% CO	twill	180	0.57
20. Warp knitted velour fabric	90% PA 10% EL	warp knit velour	235	1.56
21. Weft knitted plain fabric	98% CLY 2% EL	single jersey	172	1.21
22. Taffeta	100% CA	plain weave	125	0.33
23. Crepe	100% PES	plain weave	85	0.25
24. Satin	100% PES	satin	125	0.30
25. Felt	100% PES	nonwoven	155	1.25
26. Organza	100% PES	plain weave	25	0.16
27. Fleece	100% PES	weft knit	250	3.99
28. Woven upholstery	100% PES	woven Jacquard	600	2.38
29. Woven outdoor leisure wear fabric	100% PES	plain weave	90	0.20
30. Tulle	100% PA	warp knitted tulle	10	0.30
31. Warp knitted tricot-satin	100% PA	warp knitted tricotsatin	100	0.40
32. leather	100% Leather	----------------	815	1.68

The second set (10 samples) was focused more on a narrower collection of men`s woollen or wool blend woven suit fabrics, weft and warp knitted blended or synthetic fabrics and fabrics containing elasthane. This set is presented in table 3.

Table 3. Specification of selected samples of the 2nd set of fabrics.

Sample Description	Fibre content	Structure	Weight g/m^2	Thickness mm
33.Men's woven suit fabric	60% WO 38% PES 3% EL	plain weave	195	0.57
34. Men's woven suit fabric	100% WO	herringbone (broken twill)	232	0.83
35. Men's woven overcoat fabric	80% WO 20% PA	modified plain weave	324	2.64
36. Men's woven overcoat fabric	59% CO 25% PAN 11% WO 5% PES	twill	460	3.23
37. Woven outdoor leisurewear fabric	100% PES	plain weave	98	0.26
38. Weft knitted jersey fabric	48% CO 48% CMD 4% EL	single jersey	208	1.09
39. Weft knitted terry fabric	55% CV 45% PES	weft knit terry	288	1.69
40. Warp knitted jersey-based fabric	100% PES	warp knit jersey-based	154	0.51
41. Warp knitted mesh fabric	100% PES	warp knit mesh	128	0.51
42. Brushed warp knitted fabric	100% PES	brushed warp knit	215	0.98

The last set (12 samples) consisted only of non-laminated and laminated synthetic warp knits that are used in automotive industry. The non-laminated samples have then been laminated to foam material with either backing fabric or not. The density and thickness of the foam material varies between the samples as well the backing material. The samples and their physical properties are presented in table 4.

Table 4. Specification of selected samples of the 3rd set of fabrics.

Sample Description	**Fibre content**	**Structure**	**Weight g/m^2**	**Thickness mm**
43. Warp knit for car seats	89% PES/ 11% EL	warp knit	278	1.22
44. Warp knit for car seats	100% PES	warp knit	168	1.10
45. Warp knit for car seats	100 % PES	warp knit	147	1.60
46. Warp knit for car seats	100% PA	warp knit	98	1.55
47. Warp knit for car seats	Face fabric: 100% PES (sample 42) Foam: E-35 PF Backing: 100% PES (sample 52)	3-layer laminate	386	4.09
48. Warp knit for car seats	Face fabric: 89% PES/ 11% EL (sample 43) Foam: E-35 PF Backing: 100% PA (sample 53)	3-layer laminate	438	4.19
49. Warp knit for car seats	Face fabric: 100% PES (sample 44) Foam: E-35 PF Backing: 100% PES (sample 52)	3-layer laminate	335	4.11
50. Warp knit for car seats	Face fabric: 100 % PES (sample 45) Foam: L30PS Backing: 100 % PES	3-layer laminate	332	3.54
51. Warp knit for car seats	Face fabric: 100% PA (sample 46) Foam: E-25 TX	2-layer laminate	170	4.03
52. Backing	100% PES	warp knit	53	0.42
53. Backing	100% PA	warp knit, interlock	121	0.81
54. Warp knit for car seats	Face fabric: 89% PES/ 11% EL (sample 43, different colour) Foam: L30PS	2-layer laminate	287	3.35

4 EXAMPLES OF TEST RESULTS

The mechanical properties of the samples were determined using the standard settings of KES-F bending, tensile, compression, shear and tensile and surface friction and roughness measurements [1]. The settings were changed according to the material when it was necessary. The tensile properties were also measured using the Testometric

M-500 tensile tester and a special five force step elongation-relaxation program. The variations of the results of these different fabric sets are analysed.

4.1 KES-F Bending

The bending rigidity (B) describes how easily the material bends when the test piece is bended in perpendicular to the warp and weft directions. The hysteresis (2HB) indicates the recoverability of the material from the bended state. The bending is not possible to determine for samples thicker than 3 mm, therefore only one laminated sample from the 3rd set was measured. The value ranges of the results are presented in table 5. A low value means that the material has low resistance to bending.

Table 5 The value ranges and the lowest and the highest values for B ($gf*cm^2/cm$) in warp/machine and in weft/cross directions.

	Range		Lowest value	Highest value
	warp/machine	weft/cross		
1st set	0.004-3.964	0.002-6.479	Sample 31 (warp) and 17 (weft)	Sample 32 (warp) and 10 (weft)
2nd set	0.015-0.843	0.014-0.622	Sample 39	Sample 36 (warp) and (weft)
3rd set	0.006-0.040	0.006-0.061	Samples 46, 52, 53 (mach) and (cross)	Laminated sample 54 (0.998) and (0.781)

The value range is much wider for the 1st fabric set than for the 2nd and the 3rd sets. However in the 3rd set the highest value has the laminated sample and it is higher than the highest for the 2nd set of fabrics. The thin knitted samples have the lowest values and the thick woven sample, leather sample and laminated sample have the highest bending rigidity values.

4.2 KES-F Compression

The compression test has several characteristic values: the linearity (LC), compressional energy (WC) and resilience (RC) as shown in table 1 and in addition thicknesses at compression pressures of 0.5 (T_0) and 50 or 25 (T_m) g/cm^2 are recorded and compression rate ($EMC = (T_0-T_m)/T_0$) is calculated. Here we examine the value ranges of results for resilience (RC) in table 6 and compression rate (EMC) in table 7. The laminated samples of 3rd set have been measured only using a lower compression pressure of 25 g/cm^2 because with higher pressure the measuring range was exceeded.

Table 6. The value ranges and the lowest and the highest values for RC (%).

	Range		Lowest value	Highest value
	RC 25 g/cm^2	RC 50 g/cm^2		
1st set		36.42-93.75	Sample 4	Sample 7
2nd set		37.56-73.79	Sample 38	Sample 37
3rd set	39.92-55.81	36.97*-51.22*	Sample 46* and 53*	Sample 49 and 52*
- non-laminated	*39.92-50.27*			
- laminated	*44.82-55.81*			

**non-laminated samples*

A high value for resilience signifies that the return curve of compression follows near the compression curve. The range is widest for the 1st set of fabrics when comparing the ranges of the pressure of 50 g/cm^2. When comparing the laminated and non-laminated samples of the 3rd set the laminated have higher resilience values.

Table 7 The value ranges and the lowest and the highest values for compression rate EMC (%).

	Range		Lowest value	Highest value
	RC 25 g/cm^2	RC 50 g/cm^2		
1st set		5.36-53.08	Sample 32	Sample 14
2nd set		13.73-43.56	Sample 40	Sample 35
3rd set	7.9-38.1	22.7*-48.3*	Sample 48 and 52*	Sample 46* and 44*
- non-laminated	16.05-38.06			
- laminated	7.88-18.36			

**non-laminated samples*

The value ranges of compression range show that the most versatile fabric selection has the widest range also. The laminated samples in the 3rd set have lower values than the non-laminated of the same set at compression pressure of 25 g/cm^2. The compression rate is higher when using higher pressure. For resilience values there is no logic tendency for the difference.

4.3 KES-F Surface Roughness

The surface roughness (SMD) is the mean deviation of the thickness of the sample when a steel pianowire contactor of diameter of 0.5 mm travels on the fabric surface at a certain speed a certain length [1]. The roughness was measured for all the samples of the different sets. However, the very thick, voluminous, uneven and/or easily stretchable materials were difficult to measure, and some of the results had to be discarded, e.g. samples 52 and 54. The value ranges of the results for the mean deviation of surface roughness SMD are presented in table 8. Only one sample from the 1st set was measured on back side as well.

Table 8 The value ranges and the lowest and the highest values for surface roughness SMD (μm).

	Range		Lowest value	Highest value
	warp/machine	weft/cross		
1st set face	0.421-16.960	1.335*-24.815*	Sample 24 and 29*	Sample 28 and 3*
back	6.670	12.683	Sample 28	Sample 28
2nd set face	3.08-14.51	1.26*-12.13*	Sample 42 and 37*	Sample 36
back	3.10-18.61	1.15*-14.15*	Sample 42 and 37*	Sample 40 and 36*
3rd set face, non-laminated	2.368-9.690	3.800*-9.668*	Sample 53 and 43*	Sample 45
face, laminated	2.253-8.419	2.175*-7.240*	Sample 47 and 48*	Sample 48 and 50*
back, non-laminated	2.235-8.313	1.605*-34.307*	Sample 53 and 43*	Sample 45
back, laminated	1.580-9.858	2.303*-10.245*	Sample 48	Sample 47 and 49*

The value range is widest for the 1st fabric set and for the non-laminated samples of 3rd set on back side when looking at the results in warp and weft direction altogether. The values are at a little lower level for laminated than for non-laminated samples when comparing the right side of the 3rd set of fabrics.

4.4 KES-F Surface Friction

The surface friction is measured using the same equipment as for roughness but the 5 mm wide sensor consists of ten piano wires piled together forming a larger contact area than for roughness measurement [1]. The measured parameters are the mean value of the coefficient of friction (MIU) and mean deviation of coefficient of friction (MMD). Low value for MIU corresponds low friction and low value for MMD indicates that MIU value is even. The value ranges and the lowest and the highest values for MIU are shown in table 9.

Table 9 The value ranges and the lowest and the highest values for MIU (-).

	Range		Lowest value	Highest value
	warp/machine	weft/cross		
1st set face	0.103-0.408	0.115*-0.419*	Sample 18	Sample 27 and 16*
back	0.260	0.292	Sample 28	Sample 28
2nd set face	0.139-0.376	0.144*-0.321*	Sample 41 and 34*	Sample 39
back	0.146-0.345	0.147*-0.305*	Sample 34	Sample 36 and 39*
3rd set face, non-laminated	0.203-0.355	0.229*-0.298*	Sample 52 and 44*	Sample 43 and 45*
face, laminated	0.365-0.574	0.341*-0.512*	Sample 51 and 49*	Sample 54
back, non-laminated	0.163-0.269	0.202*-0.302*	Sample 44	Sample 52and 53*
back, laminated	0.275-2.620	0.302*-2.531*	Sample 47 and 50*	Sample 51

The first set of fabrics has wider range of friction values than the second set of fabrics and the non-laminated third set of fabrics. The highest values are for weft knitted fleece, lurex knit, terry knit, woven twill, pile warp knit and foam backing samples. The lowest values have samples for woven polyurethane coated synthetic fabric, woven calendered herringbone fabric, warp knit mesh fabric and some pile warp knits that are laminated or have flattened pile. When comparing the non-laminated face fabrics to the laminated fabrics on the right side the laminated have clearly higher values than the non-laminated ones.

4.5 KES-F Tensile

The tensile test characteristic values are linearity (LT), tensile energy (WT), resilience (RT) and max. extension (EMT) [1]. The value ranges of the results of the maximum extension (EMT) are gathered in table 10. Due to the high extensibility of some samples the measurements were made using sample lengths of 25 and 50 mm.

Table 10 The value ranges and the lowest and the highest values for extensibility, the strain at 500 gf/cm, EMT (%).

	Range		Lowest value	Highest value
	warp/machine	weft/cross		
1st set 50 mm	1.112-85.877	0.700*-79.714*	Sample 18 and 9*	Sample 20 and 17*
2nd set 25 mm**	6.004-49.803	2.295*-73.195*	Sample 37	Sample 38
50 mm ***	3.388-16.562	1.303*-17.333*	Sample 37	Sample 33 and 35*
3rd set 25 mm**	5.994-35.570	5.117*-98.304*	Sample 50 and 47*	Sample 53 and 43*
50 mm***	6.112-33.598	3.977*-43.548*	Sample 50 and 47*	Sample 52 and 48*

**measured samples 37-39 of the 2nd set and samples 43-51, 53-54 of the 3rd set

***not measured samples 38-39 of the 2nd set and 43, 53-54 of the 3rd set

Again the 1st set samples have the widest value ranges in warp and weft directions at 50 mm sample length. Samples 37, 46, 47 and samples 48, 49 and 54 in machine direction and 44, 45 and 50 in cross direction have higher EMT values at 25 mm sample length than at 50 mm sample length.

4.6 KES-F Shear

The shear properties were measured using the KES-F tensile tester unit shearing the rectangular shape test piece at a max. angle of 8 degrees to the right and then to the left. The characteristic values for shear are the shearing stiffness (G) and the hysteresis values at shearing angles of 0.5 degrees (2HG) and of 5 degrees (2HG5) [1]. The value ranges of the results of the (G) shear stiffness are gathered in table 11.

Table 11 The value ranges and the lowest and the highest values for (G) shear stiffness (gf/cm*°).

	Range		Lowest value	Highest value
	warp/machine	weft/cross		
1st set	0.179-30.998	0.176*-31.582*	Samples 7 and 26*	Sample 32
2nd set	0.488-2.567	0.459*-2.538*	Sample 39	Sample 41
3rd set non-laminated	0.390-3.608	0.310*-3.398*	Sample 53	Samples 45 and 44*
laminated	1.961-9.891	1.862*-8.635*	Sample 54	Sample 50

The 1st set of samples has the widest value range for shear stiffness. The laminated samples have higher stiffness values than the non-laminated samples. The lowest values are indicated for woven silk and organza fabrics, knitted terry and warp knitted backing fabrics and for a two-layer laminate. Highest values are recorded e.g. for leather and a three-layer laminate samples.

4.7 Step-tensile

The characteristic value for step-tensile was the elongation (mm) recorded at five force steps as shown in figure 1. This figure shows also an example how the elongation properties and the shape of the curve of the non-laminated cover fabric sample 42 differ from the properties and the curve of the same fabric when laminated to foam with backing material, called sample 47. The hysteresis of the curve is larger for sample 42 than for sample 47.

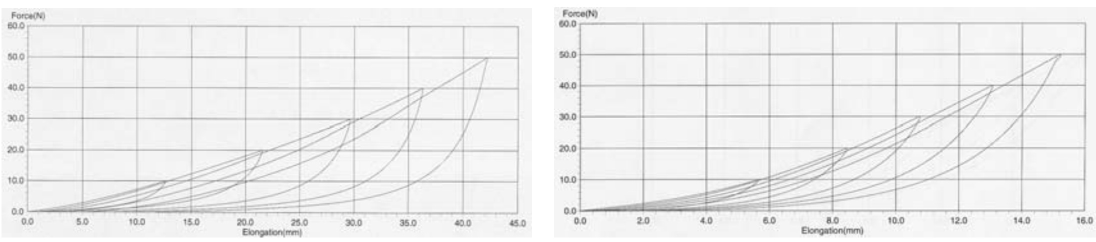

Figure 1 The step-tensile of non-laminated sample 42 (max. value 42 mm) and laminated sample 47 (max. value 15 mm) in machine direction.

The value ranges at 10 N and at 50 N and the samples that have the lowest and the highest values for elongation (mm) are gathered in table 12.

Table 12 The value ranges and the lowest and the highest values for elongation (mm).

	Range from at10N to at50N		Lowest value	Highest value
	warp/machine	weft/cross		
1st set*	0.77-114.81	0.48*-150.31*	Samples 10, 9*	Samples 21, 16*
2nd set**	1.75-70.00	0.745*-107.08*	Sample 37	Sample 38
3rd set** non-lamin.	12.545-59.496	3.603*-194.825*	Sample 42	Samples 45, 43*
laminated	5.323-43.859	2.887*-179.905*	Sample 47	Sample 54

*one parallel measurement, **mean value of two parallel measurements

The 1st set samples have the widest range in warp direction. In cross direction the 3rd set samples have the highest values.

5 DISCUSSION AND CONCLUSIONS

The received KES-F and step-tensile results will be compared to the results of subjective evaluation. Preliminary subjective evaluation has been performed but some parallel evaluations will be made before further analyses.

The results will be used by other partners for simulating the tensile and shear behaviour of virtual fabric. The results of surface properties will be exploited in the tactile context and they will imitate the surface properties of different types of structures by vibrating at the typical amplitudes of the surface. The haptic context also uses the tensile properties of fabrics by giving force feedback typical for the fabric.

The KES-F system has certain weaknesses in this project context. The system is quite stiff and there is not much modification possibilities.

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