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Tearing of knicker fabrics

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ABSTRACT

In Dunedin (South Island, New Zealand), a sexual assault is reported to police approximately once every two to three weeks, with some reports fictitious. Identifying a fictitious claim is difficult, and damage to apparel, especially knickers, may be the only form of evidence. In this paper, the tear behaviour of three knit fabrics, typical of those used to manufacture knickers is reported: the effect of laundering prior to tearing was considered. Tearing behaviour was determined using an Instron universal testing machine (Model 4464) operating in tensile mode to eliminate variability which is inevitable with human participants. Cotton and cotton-rich fabrics were more difficult to tear than modal-rich fabrics: the addition of elastane increased the time for the tear initiation as elastane fibres allowed the fabric to extend more before breaking. Specimens behaved differently depending on which direction they were torn (course-direction specimens down the length of the specimen, wale-direction specimens 50% down the length, 50% across the specimen). Laundered fabrics required less force to tear than new fabrics, therefore, when examining torn apparel, the fibre content and age of the garment need to be considered. Torn fibre ends appeared similar to those damaged by other means (e.g. knife, screwdriver) and no features visible under FESEM could be attributed solely to tearing damage in the fabrics studied.

1. Introduction

In New Zealand sexual offences (including but not limited to rape, attempted rape, indecent assault, obscene exposure) accounted for 1% of crime between 1994 and 2005, but such crimes are believed to be the most under-reported offences (fewer than one in ten sexual assaults) [1]. A study of 153 cases conducted by Doctors for Sexual Abuse Care (DSAC) in Dunedin (South Island, New Zealand) established that a sexual assault is reported to police every two to three weeks and 99% of reported cases involved female victims aged from 8 to 85 years. A typical attack in Dunedin involves a male attacker, occurs between midnight and 08:00 (56%), involves alcohol (60%), and the victim has some acquaintance with the assailant (80%).[2]

False criminal reports are a reality for law enforcement officials, waste police, forensic and judicial resources and can lead to possible miscarriage of justice [2,3]. Identifying a fictitious sexual assault claim is difficult, and often damage to apparel is the only form of forensic evidence [2]. Damage to underwear in alleged sexual assault cases, including knickers, is often observed. Knickers are "a woman's or girl's undergarments covering the body from the waist or hips to the top of the thighs and having leg-holes or separate legs" [4].

Apparel worn during an alleged assault will usually have been laundered prior to the event. Additionally, that apparel may be laundered in an attempt to remove evidence, or the experience itself (in the case of sexual assault, the latter is more likely) [5]. Laundering new fabrics leads to dimensional changes which alter properties of the fabric (e.g. mass per unit area, thickness) [6,7]. Thus forensic experiments should not be carried out on new fabrics [8]. Understanding the effect of laundering on fabrics and on fabric damage is thus critical [5,9].

In the context of forensic examinations, the most frequent damage to apparel is reportedly that caused by ripping/tearing; cutting with scissors; slashing, or stabbing with a knife; and from the discharge of a firearm [10]. A number of factors affect severance morphology in damaged fabrics e.g. fibre content, fabric structure, agent used (e.g. knife, scissors, hammer, screwdriver, tearing), number of layers of apparel or fabric, level of degradation or laundering, and the presence of fluid [5,9–15]. Understanding damage to apparel is important to support criminal investigations. Damage to knicker fabrics does not appear to have been systematically investigated previously.

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Tearing fabric reportedly results in markedly different morphological features compared to other severance types, and is affected by fibre type and fabric construction [13,15]. Knitted fabrics may tear according to the direction of the worked yarn (e.g. warp or weft knit). Monahan and Harding [13] reported difficulties tearing knitted fabrics (T-shirt and sweatshirt, both polyester/cotton, double knit). Tears along the 'warp direction' (wale) resulted in 'right-angled tears', the tear not proceeding along the intended direction but along the 'weft' (course).

Previous studies on tearing apparel and/or fabrics have (or are assumed to have) involved tearing specimens by hand, thus introducing variability [13–15]. Tensile testers apply a constant rate of extension, creating consistent test conditions among samples. Tensile testers will not, of course, recreate a scenario of how damage was caused. However, forensic scientists need to understand how apparel behaves under known conditions and with several variables, before being able to interpret evidence.

The aim of this work was to investigate (i) the tearing behaviour of fabrics commonly used to manufacture knickers available in New Zealand, (ii) the effect of laundering on tearing fabrics, and (iii) the appearance of damage caused by tearing.

2. Materials and methods

Three single jersey fabrics commonly used in the production of knickers available in New Zealand were selected: (i) 100% cotton (cotton), (ii) 92% cotton/8% elastane (cotton/elastane blend), and (iii) 92% modal/8% elastane[3] (modal/elastane blend). Fabrics were laundered and dried flat prior to specimen preparation [6,16]. Three levels of laundering were selected (0, 6, and 60 cycles) to represent new, used and old fabrics. Specimens were prepared and tested in standard conditions (20 ± 2 °C, 65 ± 4% R.H.; 24 h) [17]. No specimens were cut containing the same wale or course, nor were they cut within 50 mm of the manufactured edge [18]. Mass per unit area, thickness and number of stitches per 10 mm were recorded ($n = 5$, 100 mm × 100 mm) [19–21]. Dimensional change following laundering was calculated ($n = 5$, 500 mm × 500 mm) [22].

Specimens were prepared in both wale and course directions ($n = 5$, Fig. 1) [23]. Tear tests were conducted using a bench-mounted Instron Universal Tester (Model 4464) fitted with a 100 N load cell, a test speed of 100 mm/min, with grips tightened to 15 N m (Fig. 2). Tear tests were conducted until either the tear reached the end point or specimen failure occurred (i.e. specimen being torn in two pieces prior to reaching the end point). Specimens were tested in randomised blocks: each block contained one replicate of each combination. Reference specimens ($n = 5$, 100% polyester, single jersey, 141 g/m^2, 0.56 mm thick, wale direction) were tested before and after each block to identify if data were affected by variations in environmental conditions, equipment or operator during the test procedure.

Force (N) vs. time (s) (no filters applied; 1000 points/s) data from the tear tests were collected digitally using a Powerlab® and LabChart 7®. Data for each specimen was graphed and peaks were defined as described in BS EN ISO 13937:2000 [23]. The area between the first and last peaks was divided into quarters (Fig. 3a). The first and fourth quarters were discarded as described in BS EN ISO 13937:2000 [23] and the remaining values for peak height used to calculate tear force. Tear force is defined as "Force required to propagate a tear initiated under the specified conditions" [23], hence the use of data from the second and third quartiles only.

In addition to tear force (and a deviation from the standard test method), data associated with tear initiation were obtained using macros written in Visual Basic version 6.5 [24]. Initiation of tearing was identified as being of interest in forensic investigations. Parameters for initiation to tear were calculated for each specimen (Fig. 3b):

(i) Force to initiate tear (N) was defined as the difference between the threshold force and the force at first tear point. The threshold force being the baseline force plus 4 standard deviations of the baseline force; the baseline force was taken as the mean of the first 500 data points collected. Force at first tear point was the mean of the single force point at first tear and the nineteen prior force points to account for 'noise' in the data.
(ii) Time to initiate tear (s) was calculated as the difference of the time data associated with the threshold force and the force at the first tear point.
(iii) The energy to initiate tear (J) was estimated using Simpson's rule applied between the time at threshold and the time at first tear point; adjusted for the baseline (time increment = 1 ms) [25].

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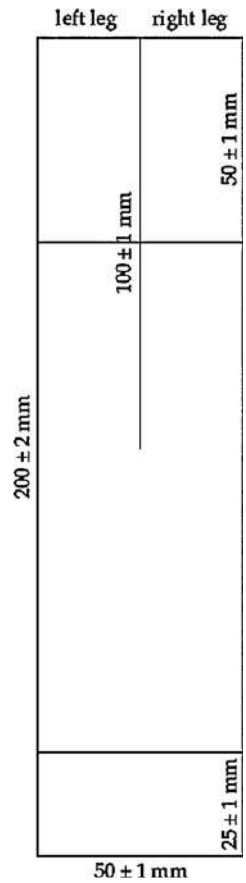

Fig. 1. Test specimen template.

Descriptive statistics (mean($\bar{x}$)), standard deviation (S.D.) and coefficient of variation (CV (%)) were calculated for structural (mass per unit area, thickness, stitches per 10 mm and dimensional change) and mechanical (force to initiate, time to initiate and energy to initiate tear and tear force) properties. The effect of fabric type, laundering and direction on data (excluding dimensional change) was investigated using univariate analysis of variance (ANOVA) and Tukey's tests (SPSS Statistics 17.0). Tear force, time to initiate and energy to initiate data were transformed ($\log_{10}$) to comply with normality and homogeneity of variance conditions required for the use of ANOVA. Dimensional change was analysed using repeated measures ANOVA [26].

Torn specimens were photographed using a Sony DSLR-A200 digital camera. Selected torn specimens were examined using a JEOL 6700 field emission scanning electron microscope (FESEM; ×35, ×750, ×1000, ×2000; 10 μA; 1.5 V). The aim of the FESEM analysis was to determine whether difference among torn fibre ends could be identified and possibly attributable to laundering condition or fabric type. Specimens were removed from the middle of the tear to avoid potential change caused by the initiation or cessation of the tear test. Specimens were mounted, technical face up, on 25 mm aluminium stubs with double-sided carbon tape and sputter coated with a 20 nm thick layer of gold palladium using an Emitech K575x Peltier-cooled high resolution sputter coater.

3. Results

3.1. Fabrics

3.1.1. Structural properties (Table 1)

Mass per unit area, thickness, number of stitches per 10 mm and dimensional stability (in the wales direction) varied among fabrics ($F_{2,36} = 444.53$, $p \leq 0.001$; $F_{2,36} = 306.33$, $p \leq 0.001$; $F_{2,36} = 1401.81$, $p \leq 0.001$; $F_{2,36} = 824.04$, $p \leq 0.001$; $F_{2,12} = 72.58$, $p \leq 0.001$). Laundering caused physical changes to the fabrics. Mass per unit area increased while thickness generally decreased ($F_{2,36} = 23.71$, $p \leq 0.001$; $F_{2,36} = 7.54$, $p \leq 0.01$). After 6 cycles the number of stitches in the wale direction increased, however,

Fig. 2. Instron universal test machine – tear test set-up.

further laundering reduced the number of stitches; there was no effect in the course direction ($F_{2,36}$ = 11.35, $p \leq 0.001$; $F_{2,36}$ = 1.37, p = NS). Laundering affected dimensional change in both wale and course directions ($F_{1,12}$ = 7.00, $p \leq 0.05$; $F_{1,12}$ = 134.88, $p \leq 0.001$). In the wale direction, the cotton and cotton/elastane blend fabrics shrank approximately 6%, while the modal/elastane blend shrank approximately 3%. In the course direction, the cotton and modal/elastane blend fabrics both extended approximately 3% while the cotton/elastane blend shrank less than 1%.

3.1.2. Differences in tearing behaviour due to direction

All course direction specimens tore vertically across wales to the end point. All cotton specimens tore vertically to the marked point regardless of direction, or the number of laundering cycles. Some wale direction specimens for the cotton/elastane and modal/elastane blends did not tear vertically to the end of the test, but initially tore vertically then across the specimen to the specimen edge (e.g. Fig. 4). Increasing the number of laundering cycles reduced the number of times wale specimens containing elastane tore horizontally. For the cotton/elastane blend, all non-laundered specimens failed, three of the 6 cycle laundered specimen failed, while no specimens failed after being laundered 60 times. For the modal/elastane blend all 0 and 6 laundering cycle specimens failed, while two specimens that had been laundered 60 times failed. While around 25% of all specimens failed (i.e. tore across the specimen; n = 21 of 90), data on all specimens were used in analysis of tear properties as this best represented 'real life'.

3.2. Tearing (Table 2)

3.2.1. Force to initiate tearing

Force required to initiate tearing was affected by fabric type and test direction ($F_{2,72}$ = 104.67, $p \leq 0.001$; $F_{1,72}$ = 16.62, $p \leq 0.001$). Laundering did not affect the force required to initiate tearing ($F_{2,72}$ = 3.01, p = NS). The cotton fabric required the highest force to initiate tearing, followed by the cotton/elastane blend and the modal/elastane blend (12.12 N; 9.86 N; 6.43 N). Tearing in the course direction required higher force than the wale direction (10.13 N; 8.81 N). At least one fabric behaved differently from the others when laundered ($F_{4,72}$ = 3.88, $p \leq 0.01$). With an increased number of laundering cycles the force required to initiate tearing of the two fabrics containing elastane decreased, however, the force to initiate tearing of the 100% cotton increased.

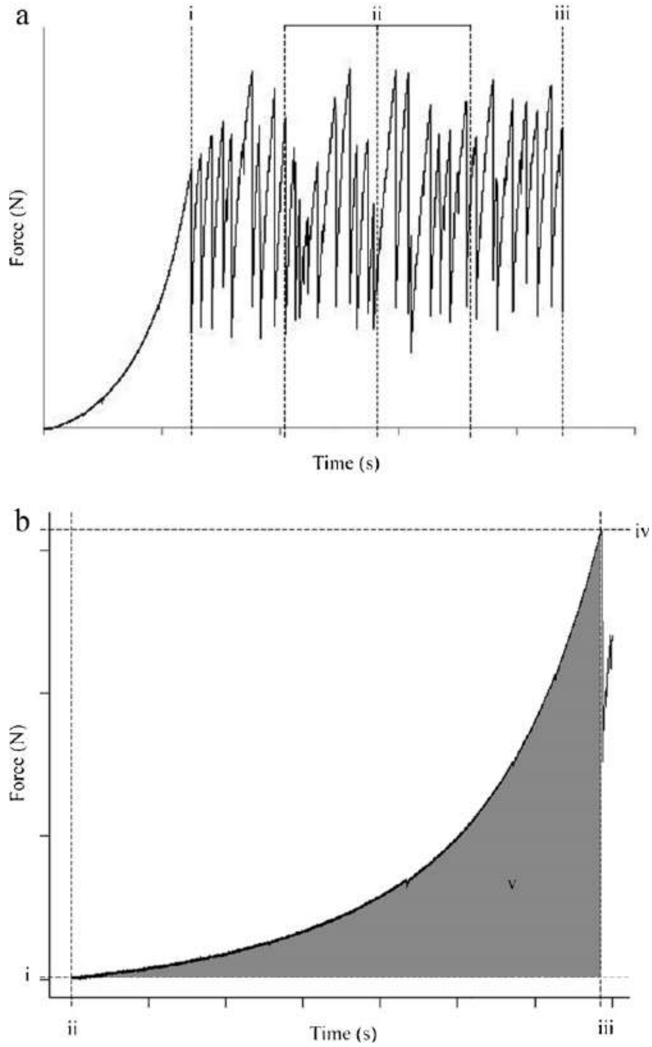

Fig. 3. Parameters for determining tear behaviour. (a) Tear force: (i) first peak; (ii) area used to calculate tear force (second and third quarters); and (iii) last peak. (b) Initiation of tear: (i) threshold force; (ii) time at threshold force; (iii) time at first peak; (iv) force at first peak; and (v) area under force-time curve, shaded area used for calculation of energy to initiate tear.

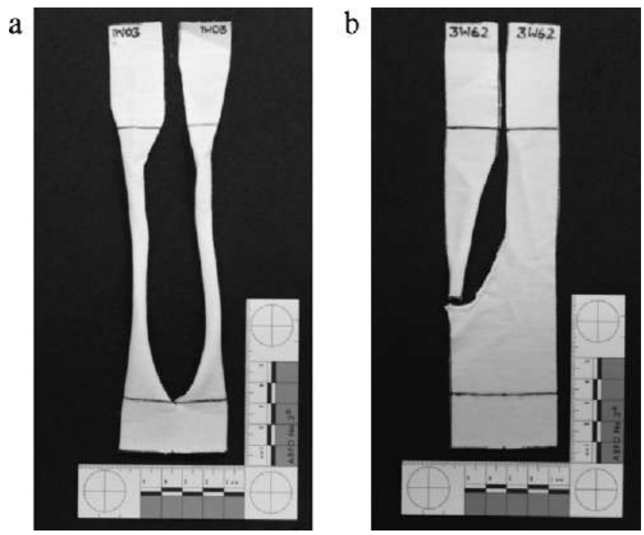

Fig. 4. Determining tear behaviour of single jersey wale specimens: (a) torn to test completion and (b) failed prior to test completion.

Table 1
Structural properties of fabrics.

Fabric	Fabric direction	Laundering cycles	Mean	S.D.	CV (%)	Min.	Max.
Mass per unit area (g/m^2)							
Cotton		0	175.86	1.61	0.92	174.22	177.80
		6	181.65	0.78	0.43	180.83	182.64
		60	180.92	1.98	1.09	178.71	184.02
Cotton/elastane blend		0	194.48	0.79	0.41	193.49	195.35
		6	210.76	2.09	0.99	209.00	214.17
		60	215.10	3.03	1.41	210.81	218.93
Modal/elastane blend		0	218.66	3.09	1.41	214.97	222.30
		6	219.81	4.52	2.06	215.05	225.98
		60	218.05	8.50	3.90	209.75	230.62
Thickness (mm)							
Cotton		0	0.80	0.01	1.25	0.78	0.81
		6	0.80	0.02	2.50	0.78	0.82
		60	0.76	0.02	2.63	0.75	0.79
Cotton/elastane blend		0	0.92	0.01	1.09	0.90	0.92
		6	0.95	0.02	2.11	0.92	0.96
		60	0.96	0.02	2.08	0.94	0.98
Modal/elastane blend		0	0.89	0.02	2.25	0.87	0.91
		6	0.81	0.01	1.23	0.79	0.82
		60	0.81	0.03	3.70	0.78	0.86
Number of stitches per 10 mm							
Cotton	Wales	0	16.0	0.00	0.00	16.0	16.0
		6	16.6	0.55	3.31	16.0	17.0
		60	16.2	0.45	2.78	16.0	17.0
	Courses	0	12.0	0.00	0.00	12.0	12.0
		6	11.8	0.27	2.29	11.5	12.0
		60	11.7	0.27	2.31	11.5	12.0
Cotton/elastane blend	Wales	0	26.6	0.55	2.07	26.0	27.0
		6	29.2	0.45	1.54	29.0	30.0
		60	28.4	1.14	4.01	27.0	30.0
	Courses	0	15.8	0.45	2.85	15.0	16.0
		6	15.7	0.45	2.87	15.0	16.0
		60	16.0	0.00	0.00	16.0	16.0
Modal/elastane blend	Wales	0	27.6	0.55	1.99	27.0	28.0
		6	28.0	1.00	3.57	27.0	29.0
		60	27.2	0.84	3.09	26.0	28.0
	Courses	0	17.6	0.55	3.13	17.0	18.0
		6	17.2	0.45	2.62	17.0	18.0
		60	17.4	0.55	3.16	17.0	18.0
Dimensional change (%)							
Cotton	Wales	0–6	−5.65	0.99	17.52	−7.16	−3.75
		0–60	−6.40	0.98	15.31	−8.07	−4.60
	Courses	0–6	1.05	1.05	100.00	−0.85	3.44
		0–60	5.15	1.13	21.94	2.56	7.06
Cotton/elastane blend	Wales	0–6	−5.87	0.54	9.20	−6.67	−4.86
		0–60	−6.68	0.73	10.93	−8.12	−5.71
	Courses	0–6	−1.01	0.51	50.50	−2.01	−0.28
		0–60	−0.86	0.71	82.56	−1.72	0.87
Modal/elastane blend	Wales	0–6	−3.54	0.52	14.60	−4.39	−2.64
		0–60	−2.84	0.70	24.65	−3.80	−1.47
	Courses	0–6	1.75	0.55	31.43	0.85	2.29
		0–60	3.76	1.02	27.13	1.42	5.16

3.2.2. Time to initiate tearing

Time required to initiate tearing was affected by fabric type, test direction and laundering ($F_{2,72}$ = 1558.55, $p \leq 0.001$; $F_{1,72}$ = 949.95, $p \leq 0.001$; $F_{2,72}$ = 19.43, $p \leq 0.001$). The cotton/elastane blend took longer to initiate tearing than the modal/elastane blend and the cotton fabric (105 s; 96 s; 49 s). In general, tearing in the course direction took longer to initiate than the wale direction (91 s; 67 s). However, differences between directions varied depending on fabric type and level of laundering, the wale specimens showing minimal change with laundering and course specimens taking

Table 2
Tearing properties of fabrics.

Fabric	Number of laundering cycles	Direction	Mean	S.D.	CV (%)	Min.	Max.
a. Force to initiate tearing (N)							
Cotton	Wales	0	11.10	2.17	19.55	9.12	14.44
		6	10.47	0.85	8.12	9.47	11.71
		60	12.56	1.71	13.61	10.66	15.29
	Courses	0	12.26	0.74	6.04	11.18	13.18
		6	13.41	1.63	12.16	11.82	15.91
		60	12.89	0.60	4.65	12.08	13.59
Cotton/elastane blend	Wales	0	9.86	2.06	20.89	7.07	11.90

Table 2 (*Continued*)

Fabric	Number of laundering cycles	Direction	Mean	S.D.	CV (%)	Min.	Max.
		6	8.85	2.27	25.65	5.32	11.13
		60	8.49	2.15	25.32	6.18	11.89
	Courses	0	11.33	1.11	9.80	10.04	12.84
		6	10.51	1.24	11.80	9.08	11.77
		60	10.14	2.62	25.84	6.85	13.61
Modal/elastane blend	Wales	0	6.67	1.70	25.49	4.08	8.67
		6	6.33	1.29	20.38	5.18	7.79
		60	4.97	0.47	9.46	4.46	5.57
	Courses	0	8.68	1.02	11.75	7.40	10.11
		6	6.87	0.28	4.08	6.54	7.18
		60	5.05	0.88	17.43	3.98	6.01
b. Time to initiate tear (s)							
Cotton	Wales	0	32.95	3.14	9.53	30.50	38.42
		6	33.50	1.12	3.34	31.80	34.57
		60	35.40	2.41	6.80	33.83	39.66
	Courses	0	66.95	3.00	4.48	62.69	70.52
		6	64.20	2.41	3.75	61.68	68.12
		60	63.51	2.00	3.15	61.41	65.98
Cotton/elastane blend	Wales	0	95.36	5.34	5.60	87.22	101.92
		6	95.67	8.77	9.17	81.23	102.54
		60	96.23	7.10	7.38	87.00	105.75
	Courses	0	122.06	4.06	3.33	117.85	127.07
		6	110.45	4.76	4.31	103.93	115.29
		60	112.23	11.33	10.10	96.74	125.65
Modal/elastane blend	Wales	0	85.25	5.98	7.01	76.36	92.51
		6	79.79	3.60	4.51	75.73	84.31
		60	72.12	1.74	2.41	70.36	74.82
	Courses	0	133.46	4.45	3.33	126.16	138.28
		6	110.28	2.00	1.81	107.97	113.35
		60	94.23	7.93	8.42	84.53	104.64
c. Energy to initiate tear (J)							
Cotton	Wales	0	0.173	0.054	31.21	0.129	0.264
		6	0.162	0.014	8.64	0.148	0.184
		60	0.212	0.042	19.81	0.174	0.284
	Courses	0	0.401	0.031	7.73	0.352	0.438
		6	0.414	0.051	12.32	0.373	0.502
		60	0.413	0.025	6.05	0.390	0.447
Cotton/elastane blend	Wales	0	0.384	0.080	20.83	0.276	0.479
		6	0.373	0.103	27.61	0.213	0.465
		60	0.386	0.105	27.20	0.270	0.550
	Courses	0	0.605	0.061	10.08	0.546	0.690
		6	0.537	0.067	12.48	0.458	0.604
		60	0.568	0.168	29.58	0.364	0.803
Modal/elastane blend	Wales	0	0.222	0.053	23.87	0.141	0.283
		6	0.210	0.040	19.05	0.175	0.263
		60	0.169	0.020	11.83	0.150	0.200
	Courses	0	0.464	0.046	9.91	0.398	0.509
		6	0.341	0.005	1.47	0.335	0.348
		60	0.249	0.054	21.69	0.185	0.317
d. Tear force (N)							
Cotton	Wales	0	14.29	1.70	11.90	12.06	16.31
		6	11.62	0.54	4.65	10.84	12.11
		60	10.40	0.17	1.63	10.18	10.65
	Courses	0	14.97	1.25	8.35	12.89	16.23
		6	13.49	1.49	11.05	11.25	15.36
		60	13.31	1.28	9.62	11.47	15.01
Cotton/elastane blend	Wales	0	14.26	1.87	13.11	12.67	17.14
		6	11.77	0.80	6.80	10.77	12.60
		60	10.58	0.31	2.93	10.06	10.85
	Courses	0	14.68	0.46	3.13	14.20	15.26
		6	14.96	0.58	3.88	14.30	15.64
		60	13.57	0.46	3.39	13.13	14.19
Modal/elastane blend	Wales	0	10.62	0.64	6.13	9.89	11.34
		6	10.46	0.60	5.74	9.46	11.05
		60	6.94	0.41	5.91	6.45	7.41
	Courses	0	9.35	0.43	4.60	8.72	9.87
		6	8.43	0.66	7.83	8.06	9.60
		60	6.96	0.19	2.73	6.76	7.17

longer with increased laundering ($F_{2,72} = 115.48$, $p \leq 0.001$; $F_{2,72} = 9.99$, $p \leq 0.001$). Non-laundered fabrics were different to those which had been laundered; laundering reduced time to initiate tearing (0 cycles = 89.34 s; 6 cycles = 82.32 s; 60 cycles = 78.95 s). Fabrics differed in their response to laundering ($F_{4,72} = 14.18$, $p \leq 0.001$). Both fabrics containing cotton changed little with increased laundering, while the tear in modal/elastane blend initiated earlier with increased laundering.

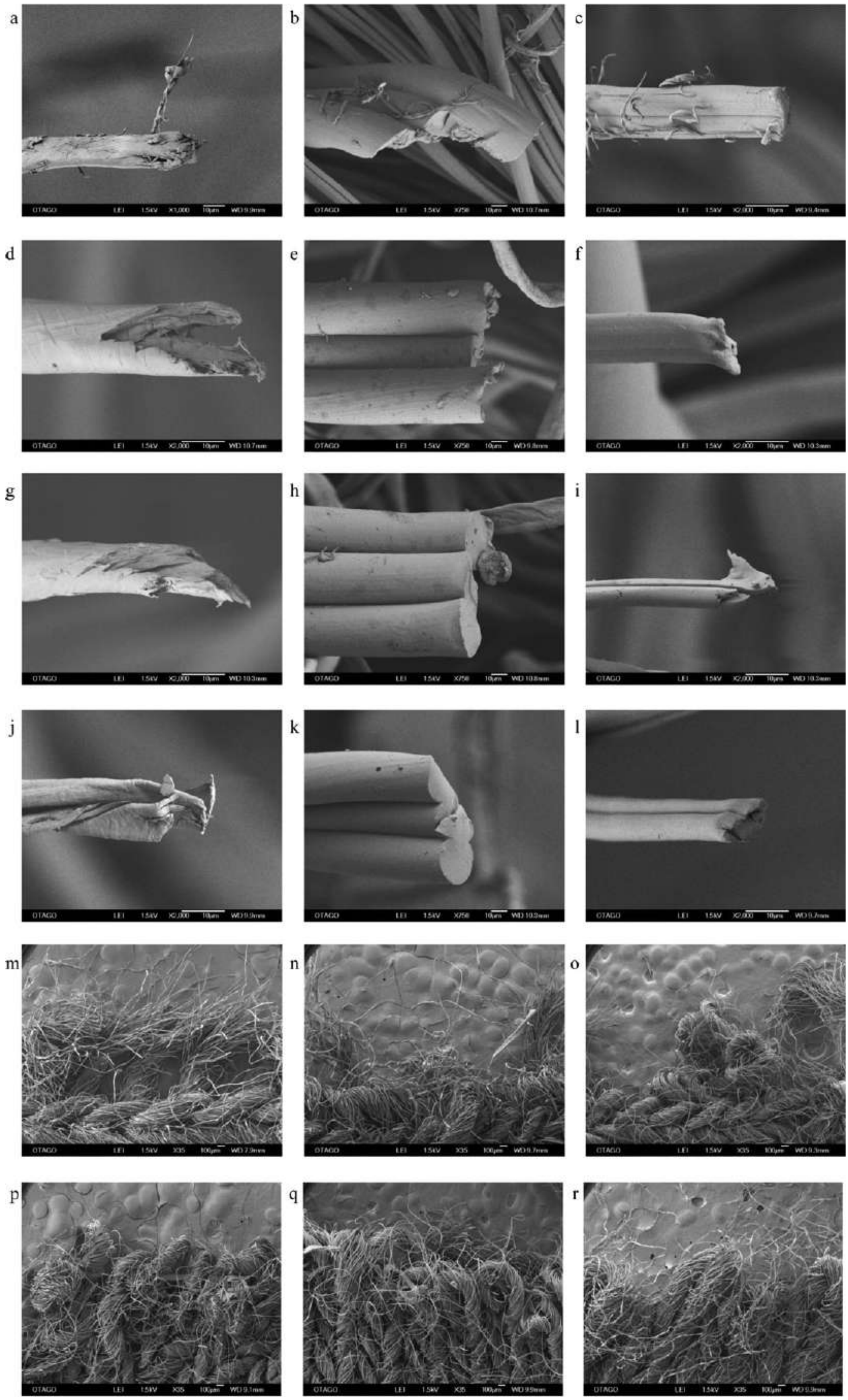

Fig. 5. Selected FESEM images. Fibrillation and peeling after 60 laundering cycles of (a) cotton; (b) elastane; and (c) modal fibres; (d, g and j) torn cotton fibre ends (×2000); (e, h and k) torn elastane fibre ends (×2000); (f, i and l) torn modal fibre ends; (m) cotton, wales, 60 cycles; (n) cotton/elastane blend, wales, 60 cycles; (o) modal/elastane blend, wales 60 cycles, torn; (p) modal/elastane blend, wales 60 cycles, failed; (q) modal/elastane blend, course, 0 cycles; and (r) cotton, course, 0 cycles.

3.2.3. Energy to initiate tearing

Energy required to initiate tearing was affected by test direction, fabric type and laundering ($F_{1,72}$ = 218.09, $p \leq 0.001$; $F_{2,72}$ = 82.48, $p \leq 0.001$; $F_{2,72}$ = 3.26, $p \leq 0.05$). Tearing in the course direction required more energy to initiate than in the wale direction (0.44 J; 0.25 J). The cotton/elastane blend required more energy to initiate tearing than the cotton or modal/elastane blend (0.48 J, 0.30 J, 0.28 J). Non-laundered fabrics require more energy to initiate tearing than laundered fabrics (0 cycles = 0.37 J; 6 cycles = 0.34 J; 60 cycles = 0.33 J). Differences between directions varied depending on fabric type ($F_{2,72}$ = 9.16, $p \leq 0.001$). Fabrics differed in their response to laundering ($F_{4,72}$ = 6.17, $p \leq 0.001$). The energy required to initiate tearing for the cotton fabric increased over the three levels of laundering. The cotton/elastane blend required similar amounts of energy over the three levels of laundering. The energy required for the modal/elastane blend decreased with increased laundering.

3.2.4. Tear force

Tear force was affected by fabric type, laundering and test direction ($F_{2,72}$ = 329.71, $p \leq 0.001$; $F_{2,72}$ = 96.21, $p \leq 0.001$; $F_{1,72}$ = 21.22, $p \leq 0.001$). The cotton and cotton/elastane blend required a similar force to tear, while the modal/elastane blend required less (13.01 N, 13.31 N, 8.79 N). Generally, specimens in the course direction were stronger (i.e. more resistant to tearing) than in the wale direction (12.19 N, 11.22 N, respectively). However, differences in direction were dependant on fabric type and the level of laundering ($F_{2,72}$ = 37.04, $p \leq 0.001$; $F_{2,72}$ = 11.97, $p \leq 0.001$, respectively). The cotton and cotton/elastane blend were stronger in the course direction than the wale direction, whereas the modal/elastane blend was stronger in the wale direction. Both the wale and course directions required similar force to tear when the fabric was new. Laundering lead to a reduction in tear force; the reduction in the wale direction was greater than the course direction. Tear force decreased for all fabrics when laundered, however, fabrics differed in their response to laundering (0 cycles = 13.03 N; 6 cycles = 11.79 N; 60 cycles = 10.29 N; $F_{4,72}$ = 8.97, $p \leq 0.001$). The cotton/elastane blend became steadily weaker with increased laundering cycles; the cotton fabric had the largest decrease between 0 and 6 laundering cycles; the modal/elastane blend had the largest decrease between 6 and 60 laundering cycles.

3.3. Visual assessment (Fig. 5)

Fabric and fibres degraded with laundering, with fabrics exhibiting fibrillation and peeling after 60 cycles. Fibre damage which could be attributed to laundering was evident at the torn edge only on fibres which were part of the external surface of the fabric. Fibres on the inside of the fabric were assumed to not have been as exposed to the mechanical forces of the washing machine. Cotton specimens had more uniform (i.e. more regular) tear edges than specimens containing elastane. Loops and loose yarns at the severance edge were seen in specimens torn in the course direction; a similar appearance was evident with failed wale specimens. Wale specimens which tore to completion had more uniform edges that those which failed. There was no visible difference in fibre end morphology between wale and course directions. Modal fibres were the most variable in morphology of the fibre end. Differences were visible between failed and torn specimens at the macroscopic and ×35 magnification. Under magnification the direction of the tear in failed specimens did not follow the wales, instead tearing across them at an angle leaving a more uneven edge. Individual fibre ends showed no visual difference that could be attributed to directionality.

4. Discussion

Three points warrant discussion: (i) experimental method, (ii) effect of laundering and (iii) tearing behaviour in knicker fabrics.

4.1. Experimental method

One limitation of the standard test method used is that only a mean tear force value is calculated. If the requirements to initiate a tear are greater than what can be produced by a given scenario, it may be possible to comment about the likelihood of the event occurring. Minimum values will also be important for the same reasons. Therefore, in this study properties describing the initiation of the tear, including the force, time and energy required were calculated. Minimum and maximum values were also reported for all factors.

Notwithstanding the desirable features of a standard test method, the present study cannot be considered to represent a 'real event' because fabrics rather than garments were used, the latter includes elastic and seams, which may affect the tearing behaviour. Conditions such as temperature and humidity affect the behaviour of fabrics and environmental conditions at crime scenes are unlikely to be the same as laboratory conditions. The rate of extension reportedly results in changes to fibre end morphology and may have effects on the behaviour of the tear itself [27]. The rate of extension was 100 mm/min, whereas tearing knickers off a person may occur at a faster rate.

4.2. Effect of laundering

Apparel collected at crime scenes is likely to have been worn and laundered multiple times prior to the event. Hence, from a forensic perspective, it is important to understand how laundering affects the behaviour of fabrics and any damage to the fabric produced in the commission of a crime. Laundered fabrics took longer to initiate tearing than new fabrics. However, there was no difference in the force required to initiate tearing and very little difference in the energy required to initiate tearing when fabrics were laundered. Laundered fabrics had a lower tear force than new fabrics, i.e. they became weaker after laundering, this was likely to be linked to the degradation of the fibres evident in the FESEM images.

4.3. Tearing behaviour of knicker fabrics

Fabric type was the single most influential factor in all tests (both physical and measured properties) with the exception of energy to initiate tear. All three fabrics were chosen to be as similar as possible with the exception of fibre content, so differences in fabric type could be considered to be attributed to fibre content. Cotton and cotton rich fabrics were generally stronger (greater tear force), therefore, were more difficult to tear. Adding elastane to fabrics increased the time for the tear to initiate as the elastane fibres allowed the fabric to extend more before fracture. The increased time to initiate had an effect on the energy to initiate, so even though the force to initiate was lower in fabrics containing elastane, the energy required to initiate the tear was actually higher, which also corresponded to fabric thickness.

Specimens in the wale and course direction behaved differently. All course specimens tore directly down the length of the specimen. Some wale specimens tore across the specimen (failed) instead of tearing directly down. This is consistent with the findings of Monahan and Harding [13], who reported difficulty tearing down the "warp" (wale) direction, which they attributed to the garments they were testing being weft knit (the fabrics used in the current study were also weft knit). This finding is important for forensic application, because it is now known that selected weft knit fabrics can tear in both the wale and course directions under certain conditions. The course direction required a greater force, time and energy to initiate tear, and with the exception of the modal/elastane blend fabric, a greater tear force was measured, thus was harder to tear in that direction.

Damage observed in the cotton and elastane fibres was consistent with that previously published, although no published SEM images of torn knit fabrics containing modal have been identified [27,28]. Cotton-based fabrics have been used in previous studies to investigate other forms of damage (e.g. knife, screwdriver, blunt force, and ballistic) [5,9,27,29,30]. To conclusively determine if the type of damage observed using the FESEM in this study is typical of tearing damage for these fabrics, further investigation into other forms of damage would be required. For example, torn cotton fibre ends appeared similar to fibres damaged using a screwdriver [9]. Therefore the damage to cotton fibres evident in the present study cannot be attributed exclusively to one form of damage. Clean cut fibre ends were observed for elastane fibres; similar damage is usually associated with and could be mistaken for, cutting fabric with a knife [14,27,31]. Care should be exercised when considering fibre end morphology. Analysing fibre ends can be an important tool when used in conjunction with other evidence, however FESEM is an expensive, destructive method requiring specialised equipment. Images produced in this study, therefore, provide a valuable resource and contribute to broader knowledge.

5. Conclusions

Fabrics are frequently involved in forensic examinations. The three fabrics considered in this paper had a similar appearance (white, weft knit, and single jersey). However, when considering the structural properties (mass per unit area, thickness and number of stitches per 10 mm) it was clear these fabrics differed. There were also differences in the way these fabrics behaved when torn. The knicker fabrics investigated in this study did tear, although some specimens in the wale direction did not tear in the intended direction. Tearing behaviour was affected by fibre content and the level of laundering prior to tearing. This does not mean that all knicker fabrics will behave in the same way. Different amounts of laundering were required before all fabrics tore down the specimen. When examining torn apparel in a forensic context the fibre content and age of the garment (i.e. how many times it has been worn/laundered) should be considered.

Tests in this study were conducted on fabrics not garments (which include seams and embellishments such as lace and elastic). Thus, results from this study may not be appropriate to apply to actual garments. However, this study was intended to create a baseline of knowledge, and results confirm the need to better understand the actual tearing behaviour of knicker fabrics.

FESEM provided a useful visual tool for examining fabrics and fibres subjected to tearing as it allowed fibre ends to be examined, which would not have been possible otherwise. However, no features visible under FESEM could be attributed solely to tearing damage in the fabrics studied because (i) fibre end features varied with the type of fibre and (ii) few studies using other modes of damage on similar fabrics were available for comparison. Therefore, caution should be exercised when using fibre end morphology to identify tearing.

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