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Fiber Transfer and the Influence of Fabric Softener

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ABSTRACT: This paper reports an investigation of the influence of fabric softener on fiber transfer, using a relatively new fiber transfer abrasion tester. Nine medium-weight apparel fabrics were evaluated with and without fabric softener. Fiber transfer from these fabrics was evaluated in terms of the total number of fibers transferred, as well as the number, mean length, and length distribution of transferred fibers ≥2 mm long. Conclusions were obtained regarding the direct effect of fabric softener on fiber transfer, as well as its interactive effects with fiber denier, fabric weave, knit type, and fabric thread count. In addition, conclusions were obtained regarding mechanisms of transfer from the fabrics.

KEYWORDS: forensic science, fibers, transferring, fabric softeners

Textile materials are involved in most human activity, and it is reasonable to assume that fiber evidence is present at most crime scenes. This, of course, has been acknowledged by criminal investigators, and a survey conducted in 1983 found that 79% of crime laboratories in the United States examine fiber evidence [*1*]. One may consider typical fiber evidence to be associated with four major events—fiber transfer, persistence after transfer, evidence collection, and analysis. The initial event in this sequence is fiber transfer, the release and relocation of a fiber from its original position within a textile.

Transfer of matter between two objects when brought into contact was formally postulated in 1928 [*2*]. Experimental verification of this principle has been clearly demonstrated for fibers [*3,4*]. Various aspects of fiber transfer have been studied by textile scientists for many decades, and systematic studies from a forensic science standpoint have appeared since 1975 [*3,5*].

Fiber transfer has been evaluated several ways. A simple visual examination of basic fabric structural features may be used to obtain a qualitative measure of fiber transfer [*6*]. Quantitative measures of fiber transfer have been obtained from studies involving actual human contact [*7*]. Studies involving human contact potentially yield practical information of great value to forensic scientists. Their disadvantage, however, is a lack of control during fabric abrasion and thus a lack of experimental reproducibility. Good experimental reproducibility is necessary when comparing fabrics differing slightly in structure.

Fiber transfer has been studied quantitatively by dragging a block covered with an abrasive material over a textile's surface and then measuring the number and length of transferred fibers [*2,3,8,9*]. This simple technique provided valuable fundamental information about fiber transfer. The dominant driving force of fiber transfer was found to

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be mechanical abrasion rather than electrostatic attraction. Three transfer mechanisms resulting from mechanical abrasion were identified: release of loose fibers residing on a textile's surface, release of disentangled whole fibers partially embedded in a textile's interior, and release of fiber fragments after fracture of whole fibers. Although the use of a block to induce transfer provides more control of fabric abrasion than actual human contact, precise experimental control is still lacking.

More than 100 textile testing machines currently exist to provide quantitative measurements of fiber transfer under precisely defined experimental conditions. Unfortunately, most of these machines have been designed to abrade fabrics in an accelerated manner to shorten the testing time. For example, the Accelerotor subjects a textile to extremely rapid, high-velocity impacts resulting from contact with a metal rotor rotating at 3000 rpm and provides a measure of the mass of fibers transferred [*10*]. One must question the relevance of accelerated testing to forensic science cases, which involve typical human activity, where abrasion rates are usually substantially slower.

Many textile testing machines abrade fabrics until they achieve major structural damage, such as breaking a yarn or abrading a hole through a fabric. One must also question the relevance of these test results to situations involving only slightly damaged fabrics, which are often associated with forensic cases.

None of the previous methods of inducing fiber transfer provide the experimental control and versatility desired for studies of textile structure/fiber transfer relationships in a manner that is pertinent to typical forensic science cases. Because of these problems, we recently designed an abrasion machine which allows many experimental parameters to be varied and controlled over a wide range [*11*]. This machine is called the fiber transfer abrasion tester (FTAT). The most significant features of the FTAT are the variable abrasion load, variable abrasion rate, controlled tension on test fabrics, controlled tension on abradant materials, suitability for a wide variety of textile materials, accommodation of a wide variety of abrasive materials, orbital or linear abrasion directions, and fabric evaluation after only minimal textile structural damage has occurred.

We currently are attempting to determine basic relationships between textile structure and fiber transfer behavior using the FTAT. The textile structural features being studied include the fiber denier, fiber length, yarn size, yarn spinning method, fabric thread count, weave type, knit type, and surface contact area [*11–13*]. Our goal from these studies is to identify significant textile structural parameters that control fiber transfer and to quantify their influence. If the likelihood of fiber transfer can be better understood, fiber searches could be planned more logically with significant time savings. More importantly, the results from fiber searches could be interpreted more intelligently.

In the current paper, another structural feature is examined. We present results of carefully controlled experiments to investigate the influence of fabric softener on fiber transfer. It is well known that fabric softeners change the fabric's mechanical properties by lubricating fibers. Consequently, it is conceivable that lubricated fibers might be released more readily from textiles since their coefficient of friction is reduced in comparison with nonlubricated fibers. On the other hand, it also is conceivable that the increased mobility expected from lubricated fibers might result in more efficient sharing of applied stresses so the release of lubricated fibers might occur less readily. At any rate, the possibility of a significant change in the amount or mechanism of fiber transfer from a fabric after treatment with a fabric softener must be considered. The use of fabric softeners is common, and a better understanding of their effect on fiber transfer is relevant to the evaluation of fiber evidence.

In this study, fiber transfer from nine medium-weight fabrics was evaluated with and without a fabric softener. We investigated the direct effect of softener on fiber transfer as well as interactions between fabric softener and four other textile structural features—the fiber denier, fabric weave, knit type, and fabric thread count.

Description of the FTAT

The fiber transfer abrasion tester (FTAT) has been described in detail elsewhere [*11*], so only a brief description will be provided here. The FTAT is illustrated in Fig. 1. Abrasion occurs when the test fabric moves across a larger flat abrasive surface. The major mechanical components to control this movement include a small motor, gear box, drive pulley and belt, fly wheel, slide/dovetail, and upper and lower pads (on which the test fabric and abradant are attached, respectively). The slide/dovetail assembly allows upper pad movement in either an orbital or linear pattern over the lower pad. Orbital movement abrades a fabric in every direction and provides a composite measure of fiber transfer. Linear motion, on the other hand, abrades in only one fabric direction and may be used to study activities such as sliding into a chair or walking on a carpet in a narrow hallway.

The magnitude of the abrasive force applied to a test fabric is controlled by the mass of the upper pad. The minimum pressure attainable is 0.20 kPa (0.029 psi), and pressures several orders of magnitude larger are attainable by adding weights to the upper pad. To put this low pressure in perspective, one should note that the pressure on a person's seat while sitting in a chair is approximately 7 kPa (1 psi), and the pressure of a person's shoe while walking is approximately 70 kPa (10 psi). Consequently, the FTAT is capable of applying abrasive forces that are quite small and may provide data relevant to many mild fabric abrasions. For example, a loosely hanging suit coat rubbing against a shirt while walking constitutes a common activity that results in fabric abrasion at small pressures.

The rate at which the test fabric traverses the abradant can be varied continuously between a slow speed of 1 mm s^{-1} (1 cycle every 8 min) and a rapid speed of 150 mm s^{-1} (17 cycles every minute). These abrasion rates include the speeds at which many human motions occur and thus may provide data relevant to many human activities.

As illustrated in Fig. 2, hinges allow the upper half of the FTAT to swing open and

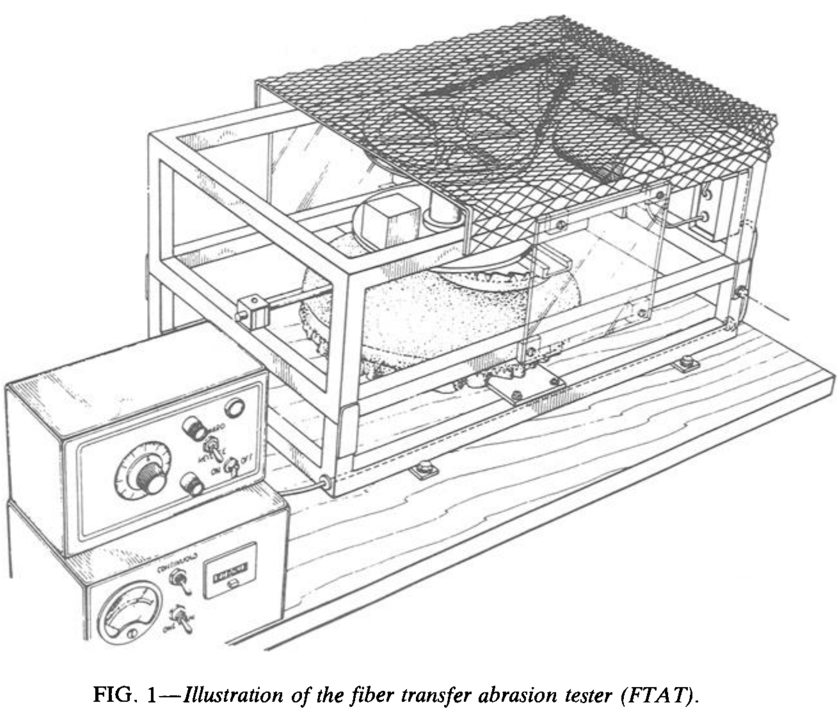

FIG. 1—*Illustration of the fiber transfer abrasion tester (FTAT).*

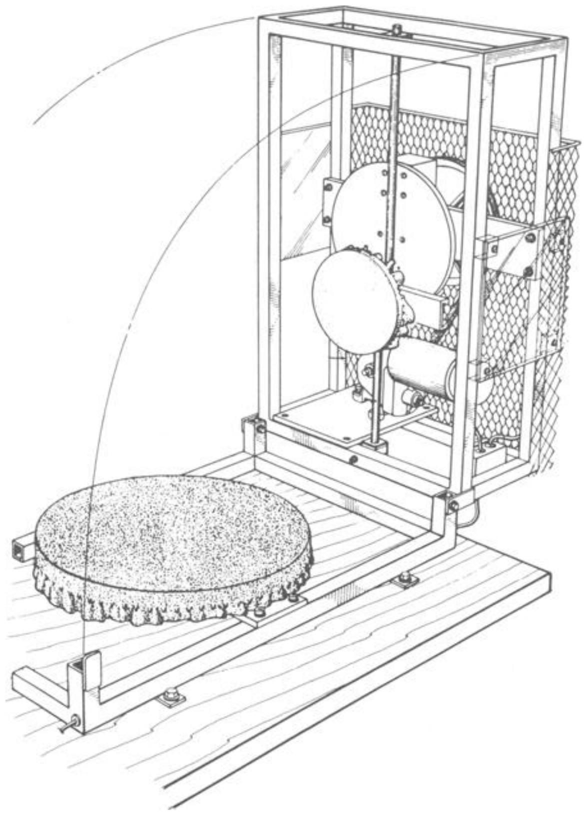

FIG. 2—*Illustration of the FTAT swung open and resting in the upright position.*

rest in an upright position for easy access to the test fabric and abradant. Access is necessary to attach test fabrics and abradant materials to the pads as well as to evaluate fiber transfer. A means of attaching test fabrics and flexible abradants to the pads with reproducible tension is illustrated in Fig. 3. A circular test fabric or abradant is pulled around the pad and hooked over metal pins on the top plate (Fig. 3*a*), and a jackscrew is torqued to separate the stretcher plates and apply tension to the material (Fig. 3*b*). This feature is desirable since research has shown that the mass of fibers lost during surface abrasion depends on the tension placed on the abraded fabric [*14*].

A wide variety of textile materials can be attached to the upper abrasion pad for testing. These include knit, woven, nonwoven, carpet, and sheer fabrics. A variety of flat abradant materials can be attached to the lower pad, including fabric, film, emery paper, or foam. In addition, other abradant materials, such as carpet, wood, metal, glass, plastic, concrete, or brick, can be secured on the platform if the lower pad is removed. The experimental control and versatility provided by the FTAT allow a variety of practical fiber transfer situations to be studied.

Experimental Procedure

Fabrics

A 100% cotton print cloth obtained from Testfabrics, Inc. (Middlesex, NJ) was used as the abradant material. Fabric-to-fabric abrasion was induced by the interaction of this

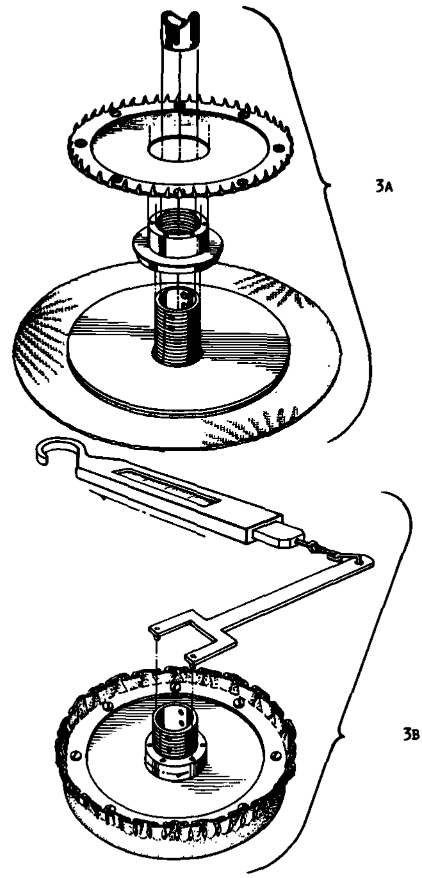

FIG. 3—*Illustration showing attachment of fabric specimen to an abrasion pad;* (a) *before attaching fabric over hooks and* (b) *during torquing of fabric.*

abradant print cloth with nine different apparel fabrics both with and without fabric softener. These nine fabrics were called donor fabrics because they were the source of the transferred fibers evaluated. Table 1 summarizes important structural features of these fabrics. Basically, they included plain, basket, and twill weaves; Birdseye and Lacoste knits; open-end spun (OE), ring spun, and textured continuous-filament (TCF) yarns; two fabric thread counts; uniform stable fiber length, multiple staple fiber length (MSL), and continuous fiber length; and two fiber deniers.

Fabric Preparation

A total of 19 different fabrics were individually prepared for testing—9 donor fabrics without softener, 9 donor fabrics with softener, and 1 abradant print cloth. Each of the fabrics was scoured separately using AATCC Test Method 124–1984 [*15*], except that an agitation time of 14 min and three 5-min rinses were used. After scouring, the print cloth abradant was dyed black to facilitate differentiation between its fibers and those transferred from donor fabrics. All the fabrics were dried while lying flat and then conditioned at 293 ± 2 K and 65 ± 2% relative humidity.

To obtain fabric softener treated fabrics, a common fabric softener was applied in the following manner: the fabric was removed from the washer after the second rinse was

TABLE 1—*Structure of donor fabrics.*

Code	Fabric Type	Yarn Type	Thread Count, yarns/cm^2	Fiber Content, polyester/cotton	Fiber Length, mm	Fiber Denier
A	plain weave	OE	...	50/50	31.8 MSL[a]	1.50
B	plain weave	OE	...	50/50	31.8 MSL[a]	1.20
C	basket weave	OE	...	50/50	31.8 MSL[a]	1.20
D	twill weave	OE	...	50/50	31.8 MSL[a]	1.20
E	twill weave	ring	58.3	65/35	38.1[b]	2.25
F	twill weave	ring	62.3	65/35	38.1[b]	2.25
G	birdseye knit	ring	...	100/0	31.8 MSL[a]	1.50
H	lacoste knit	ring	...	100/0	31.8 MSL[a]	1.50
I	basket weave	TCF	...	100/0	continuous[c]	4.50

[a]T-141 Trevira, multiple staple length.
[b]T-151 Trevira, uniform staple length.
[c]T-618 Trevira, textured continuous filament.

completed, the washer tub was filled with water for the third rinse, the amount of Downy fabric softener recommended on its container was added to the water and agitated until evenly dispersed, the fabric was then placed in the washer, and the third 5-min rinse was completed.

Abrasion of Fabrics

Donor fabrics were cut into circular specimens 0.23 m (9 in.) in diameter and tensioned on the upper pad of the abrasion machine with a torque of 1.00 N·m. The abradant fabric was cut into circular specimens 0.43 m (17 in.) in diameter and tensioned on the lower pad with a torque of 1.25 N·m. Fabric surfaces were sprayed for 30 s with compressed air delivered at 140 kPa (20 psi) prior to testing to remove loose fibers and surface debris. Abrasion was performed in an atmosphere of 293 ± 2 K and 65 ± 2% relative humidity.

Each donor fabric was subjected to only one cycle of orbital abrasion applied at a rate of 80 mm s^{-1} with the lowest pad pressure possible, 0.20 kPa (0.029 psi). These conditions were used to study fabrics rubbing with low pressure at a slow rate for only a brief time, such as might occur when a loosely hanging coat rubs against a shirt while walking.

Three different specimens from each donor fabric were tested, and a different abradant print cloth specimen was used with each donor fabric specimen. After one cycle of orbital abrasion, the print cloth abradant was illuminated with an ultraviolet lamp. Fluorescent fibers were assumed to be polyester since the polyester fibers fluoresced strongly, whereas cotton fibers from the donor and abradant fabrics fluoresced weakly or not at all. All fluorescent fibers that had transferred to the surface of the print cloth abradant were counted. This number was referred to as the total number of polyester fibers transferred.

To confirm that transferred fibers were polyester rather than cotton, the gross morphological characteristics of each transferred fiber was evaluated microscopically. Since the morphology of polyester and cotton differ markedly, this examination was considered to be an unequivocal confirmation of polyester identity.

After the total number of polyester fibers transferred had been counted, those fibers which were ≥2 mm long were retrieved from the abradant print cloth surface and secured on a microscope slide. Images of these fibers were projected onto a digitizing tablet and analyzed with computer-aided design software. This procedure allowed us to determine the number, mean length, and length distribution of transferred polyester fibers ≥2 mm long.

Results and Discussion

The total number of polyester fibers transferred from three replicate specimens of each donor fabric with and without softener is summarized in Table 2. After only one cycle of abrasion applied slowly (80 mm s^{-1}) with a very low pressure (0.029 psi), all donor fabrics made from staple fibers (Fabrics A through H) transferred hundreds of fibers. In contrast, the donor fabric made from continuous-filament fibers (Fabric I) averaged only three transferred fibers per specimen. The difference in fiber transfers from staple and continuous-filament fabrics can be explained qualitatively by considering the three transfer mechanisms discussed previously.

In general, one would expect staple fibers to transfer by all three mechanisms. However, in this study, loose fibers were removed from fabric specimens prior to testing, so little transfer would result by releasing whole fibers loose on fabric surfaces. On the other hand, staple fibers partially embedded within fabrics could be released after abrasive forces disentangled the fibers. Transfer also could occur after staple fibers were fractured once anywhere along a segment not embedded within the fabric interior. In summary, fibers could transfer from these staple fabric specimens by two of the three transfer mechanisms. On the other hand, one would expect continuous-filament fibers to transfer by only one basic mechanism. Continuous filaments span the whole fabric width, so they are mechanically secured within the fabric structure by many yarn interlacings. It would be unlikely that continuous-filament fibers would transfer by releasing whole fibers loose on the fabric surface or whole fibers disentangled from the fabric interior. Transfer must involve fracture, and two breaks would not be likely to release a fiber fragment unless they occurred within close proximity to each other.

Fabric softener substantially increased the total number of polyester fibers transferred, as is shown in Table 2. Softener increased the average number of polyester fibers transferred from staple fabrics (Fabrics A through H) from 223 to 817, a 266% increase. Softener increased the number of fibers transferred from the staple woven fabrics (Fabrics A through F) an order of magnitude more than those from the two staple knit fabrics (Fabrics G and H). Fabric softener did not increase the number of fibers transferred from the continuous-filament fabric (Fabric I). These data suggest that fabric softener changed the mechanical response of the staple fabrics in a way that increased fiber transfer, but the change was less significant for knits than for woven fabrics and was insignificant for the continuous-filament fabric.

TABLE 2—*Total number of polyester fibers transferred.*

Fabric Code	Without Fabric Softener: Mean[a]	Without Fabric Softener: Coefficient of Variation, %[a]	With Fabric Softener: Mean[a]	With Fabric Softener: Coefficient of Variation, %[a]	Change in Means, %
A	148	13	1030	11	596
B	256	19	1253	22	389
C	223	17	1094	13	391
D	398	29	1275	19	220
E	184	8	922	12	401
F	201	20	1017	29	406
G	249	24	333	22	34
H	375	5	456	9	22
I	3	173	3	33	0
A to I	226	17[b]	820	17[b]	263

[a]Mean and percent coefficient of variation for three replicate specimens of each fabric.
[b]Based on staple fabrics (A through H).

TABLE 3—*Number of polyester fibers ≥2 mm long transferred.*

	Without Fabric Softener		With Fabric Softener		
Fabric Code	Mean[a]	Coefficient of Variation, %[a]	Mean[a]	Coefficient of Variation, %[a]	Change in Means, %
A	38	25	22	18	−42
B	67	48	55	27	−18
C	78	24	61	25	−22
D	126	20	116	18	−8
E	61	21	42	26	−31
F	67	27	58	11	−13
G	17	44	23	29	35
H	62	30	42	14	−32
I	0	. . .	0.3	175	. . .
A to I	57	30[b]	47	21[b]	−17

[a]Mean and percent coefficient of variation for three replicate specimens of each fabric.
[b]Based on stable fabrics (A through H).

The variation of test results among replicate specimens differs substantially for different textile abrasion testers. The coefficient of variation among test results with the FTAT was found in a previous study to be intermediate among textile abrasion testers and was approximately 17% [*12*]. Table 2 shows that the percent coefficient of variation among three replicate specimens of each fabric also averaged 17%. Application of fabric softener did not change the replicate test variability for the staple fabrics.

The number of polyester fibers ≥2 mm long transferred from three replicate specimens of each donor fabric with and without softener is summarized in Table 3. One of the staple fiber twill weaves (Fabric D) transferred the greatest number of fibers ≥2 mm, as well as the greatest total number of fibers. The propensity of staple fiber twill fabrics to transfer a large number of fibers has been reported previously [*11,13*]. The fabric made from continuous-filament fibers (Fabric I) transferred the fewest fibers ≥2 mm long, as well as the fewest total fibers. This fabric transferred a total of only one fiber ≥2 mm. It was noted previously that transfer can occur by fracturing continuous filament fibers, but fibers must be broken twice, and the two breaks would not release a fiber fragment unless the breaks occurred within close proximity to each other. Since the distance between yarn interlacings in Fabric I was approximately 0.8 mm, a 2-mm-long fiber was secured with at least one yarn interlacing, and its release would not be straightforward. Consequently, it is not surprising to find a dearth of long fibers transferred from this fabric at a small applied pressure.

By comparing Tables 2 and 3, one can see that the majority of transferred fibers were shorter than 2 mm. That is, approximately 75% of the fibers transferred from fabrics without softener and 94% of the fibers transferred from fabric with softener were <2 mm. Since all donor fabrics were manufactured from polyester fibers that were substantially longer than 2 mm, the dominant mechanism of fiber transfer must have been fiber fracture. This is true for all nine fabrics, either with or without fabric softener. Interestingly, this result was observed even though the global pressure used to induce transfer was very small (0.029 psi). Since the tensile breaking stress of typical polyester fibers is on the order of 10^4 to 10^5 psi, stress during abrasion must have been greatly localized, so the breaking strength of fibers was readily exceeded, even at small fabric pressures.

Interestingly, fabric softener decreased the number of transferred fibers ≥2 mm by an average of 17%, even though softener increased the total number of fibers transferred by an average of 263%. This suggests that softener increased fiber fracture but decreased the release of whole fibers.

The coefficient of variation among replicate fabric specimens was greater for fibers ≥2 mm than for the total number of transferred fibers. Values averaged 30 and 21% for the number of fibers ≥2 mm, in comparison with 17% for the total number of fibers transferred. This finding is in agreement with two previous studies which found the coefficient of variation for the number of fibers ≥2 mm to be greater than that of the total number of fibers [*11,13*]. However, one previous study found the coefficients of variation of the two fiber groups to be approximately equal [*12*].

The mean length of polyester fibers ≥2 mm transferred from each fabric is summarized in Table 4. Mean fiber lengths did not vary among the fabrics as greatly as the total number or number of fibers transferred ≥2 mm. The mean length for most fabrics ranged from approximately 4 to 8 mm. The two knitted fabrics (Fabrics G and H) exhibited longer mean fiber lengths than woven fabrics, both with and without softener. Since the distances between yarn interlacings in several of the woven fabrics were at least as long as those of the knit fabrics, the greater mean length of transferred fibers from the knits probably cannot be attributed to this factor unless the knit loops were distorted more than the woven yarn floats during abrasion. This may have occurred, since the knits were considerably less stiff than the woven fabrics. However, this hypothesis cannot be proven from these data.

Softener did not seem to change the mean fiber length among the nine fabrics in a consistent way. The coefficient of variation among replicate fabric specimens for the mean fiber lengths averaged approximately 11% for fabrics, both with and without softener.

The effect of fabric softener on fiber transfer from each of the nine fabrics was evaluated statistically using the *t*-test. Fiber transfer was evaluated by computing the probability that the two means for each fabric (with and without softener) in Tables 2 through 4 were equal. These results are summarized in Table 5. Data in this table reveal that fabric softener significantly affected the total number of fibers transferred because the *P* values for seven of the eight staple fabrics were 0.03 or less. On the other hand, softener exhibited less effect on the number and mean length of transferred fibers ≥2 mm. None of the *P* values for these two measures of fiber transfer was <0.05.

An analysis of variance (ANOVA) was used to explain fiber transfer differences in terms of textile structural features (including fabric softener). This analysis also evaluated

TABLE 4—*Mean length, in millimetres, of polyester fibers ≥2 mm long transferred.*

Fabric Code	Without Fabric Softener: Mean[a]	Without Fabric Softener: Coefficient of Variation, %[a]	With Fabric Softener: Mean[a]	With Fabric Softener: Coefficient of Variation, %[a]	Change in Means, %
A	5.05	5.6	4.39	14.5	−13
B	4.72	9.9	4.62	7.9	−2
C	5.07	5.7	4.64	8.2	−8
D	5.05	3.9	5.16	4.0	2
E	5.16	6.3	5.90	8.3	14
F	4.40	13.7	4.96	6.1	13
G	7.65	16.2	6.38	27.1	−17
H	8.29	25.8	7.20	11.6	−13
I	...	...	2.01	...	...
A to I	5.67	10.9[b]	5.03	11.0[b]	−3

[a]Mean and percent coefficient of variation for three replicate specimens of each fabric.
[b]Based on stable fabrics (A through H).

TABLE 5—*Comparison of fabrics with and without fabric softener using the* t-*test.*[a]

Comparison	Total Number of Polyester Fibers	Number of Polyester Fibers ≥2 mm Long	Mean Length of Polyester Fibers ≥2 mm Long
A_{with} versus $A_{without}$	0.0002	0.0611	0.1734
B_{with} versus $B_{without}$	0.0033	0.5799	0.7851
C_{with} versus $C_{without}$	0.0005	0.2966	0.1976
D_{with} versus $D_{without}$	0.0047	0.6275	0.5381
E_{with} versus $E_{without}$	0.0004	0.1147	0.0948
F_{with} versus $F_{without}$	0.0086	0.4674	0.2294
G_{with} versus $G_{without}$	0.2012	0.4093	0.3616
H_{with} versus $H_{without}$	0.0322	0.1488	0.4589
I_{with} versus $I_{without}$	...	...	...

[a]Probability that the fiber transfer means of fabrics with and without softener are equal.

TABLE 6—*Analysis of variance* P *values for polyester fibers transferred.*[a]

Fabrics	Variables[b]	*P* Value: Total Number of Fibers	*P* Value: Number of Fibers ≥2 mm Long	*P* Value: Mean Length of Fibers ≥2 mm Long
A, B	soft	0.0001	0.2267	0.1866
	den	0.0908	0.0190	0.8499
	soft[a] den	0.5238	0.8800	0.3175
	soft, den, soft[a] den	0.0001	0.0720	0.4084
B, C, D	soft	0.0001	0.2359	0.3927
	weave	0.2224	0.0011	0.1197
	soft[a] weave	0.7695	0.9656	0.3988
	soft, weave, soft[a] weave	0.0001	0.0078	0.2406
E, F	soft	0.0001	0.0915	0.0369
	count	0.5570	0.1930	0.0113
	soft[a] count	0.6790	0.5042	0.7235
	soft, count, soft[a] count	0.0002	0.1838	0.0219
G, H	soft	0.0260	0.2784	0.2299
	knit	0.0035	0.0009	0.4417
	soft[a] knit	0.9577	0.0795	0.9246
	soft, knit, soft[a] knit	0.0084	0.0037	0.5352

[a]Probability that the fiber transfer means of the fabrics compared are equal.
[b]Structural parameters are denoted as follows: soft = fabric softener; den = fiber denier; weave = fabric weave; knit = fabric knit; and count = fabric thread count.

interactions between two or more structural features. Results of the ANOVA for four different fabric groups are summarized in Table 6: Fabrics A and B (two plain weaves varying only in fiber denier); Fabrics B, C, and D (three woven fabrics varying only in weave type); Fabrics G and H (two knit fabrics varying only in knit type); and Fabrics E and F (two twill weaves varying only in fabric thread count). The *P* values reported in this table estimate the probability that the fiber transfer from the fabrics being compared was similar.

Fabric softener significantly affected the total number of polyester fibers transferred for all four fabric groups ($P \leq 0.03$). This result is consistent with results of the individual *t*-tests reported in Table 5. Fabric softener did not affect the number or mean length of fibers ≥2 mm as strongly. However, *P* values obtained for the number and mean length of fibers ≥2 mm from Fabrics E and F were marginally affected by fabric softener, with *P* values of 0.09 and 0.04, respectively.

Fiber denier affected the total number and number of transferred fibers ≥2 mm from Fabrics A and B, as is summarized in Table 6. This conclusion makes intuitive sense, since one would expect smaller denier fibers to fracture with less applied force and thus transfer more readily than larger denier fibers. Fiber denier did not significantly affect the mean fiber length, however. The interaction between fabric softener and fiber denier was not significant. Data in Table 6 also show that fabric weave significantly affected the number of fibers ≥2 mm transferred from Fabrics B, C, and D. No interaction between fabric softener and fabric weave was observed for these fabrics. The fabric knit type also significantly affected the number of fibers ≥2 mm transferred from Fabrics G and H. The interaction between fabric softener and knit type was marginally significant for these fabrics. The fabric thread count significantly affected the mean length of fibers ≥2 mm for Fabrics E and F. No interaction between fabric softener and this structural variable was observed for these fabrics.

To gain insight into mechanisms of fiber transfer, we examined the length distribution of transferred fibers that were ≥2 mm. A composite distribution of transferred fiber lengths from all fabrics without and with softener is shown in Fig. 4. The number of fibers transferred from all fabrics decreased exponentially with increasing fiber length (R^2 = 0.86 for each curve). For all fiber lengths ≥2 mm, transfer from fabrics treated with softener was usually less than transfer from fabrics not treated with softener.

Table 1 shows that the staple fabrics used in this study were manufactured with one of two polyester fiber lengths: fibers uniformly 38.1 mm long or fibers of multiple staple lengths (MSL), having a mean length of 31.8 mm. The fiber length data in Fig. 4 were divided into two different plots in Figs. 5 and 6. Figure 5 shows the transferred fiber length distribution from fabrics made of fibers of uniform length, and Fig. 6 shows the transferred fiber length distribution from fabrics made of MSL fibers. Figure 6 exhibits deviations from the exponential length decrease and shows increased numbers of fibers at some lengths. Figure 5 does not exhibit these increases.

Transferred fiber length data from MSL fabrics plotted in Fig. 6 were further divided into woven (Fig. 7) and knitted (Fig. 8) fabrics. Figure 8 exhibits rather large deviations

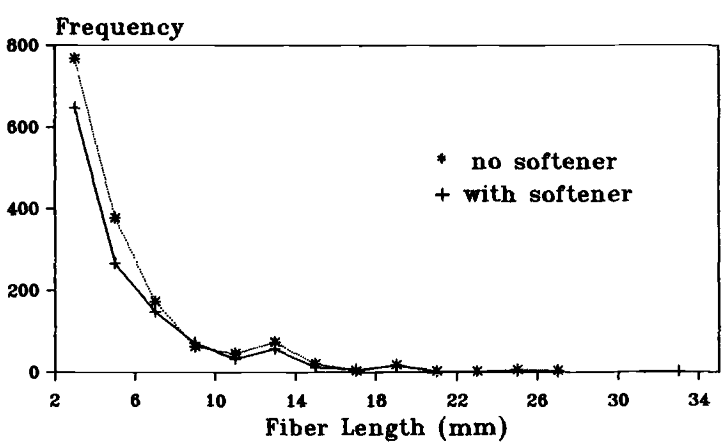

FIG. 4—*Length distribution of fibers ≥2 mm transferred—all fabrics (Fabrics A through I).*

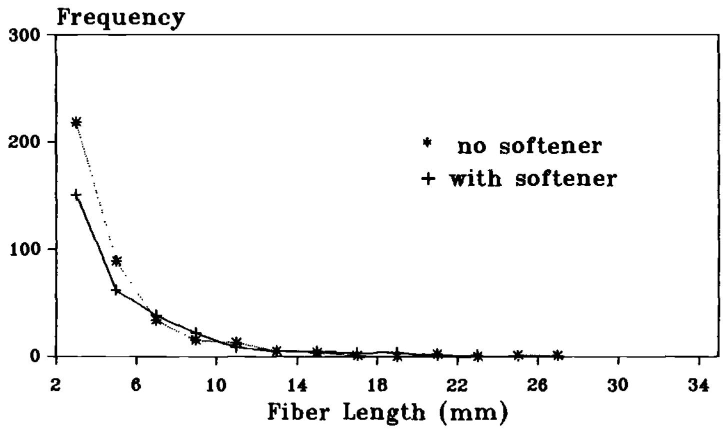

FIG. 5—*Length distribution of fibers ≥2 mm transferred—non-MSL fabrics (E, F, and I).*

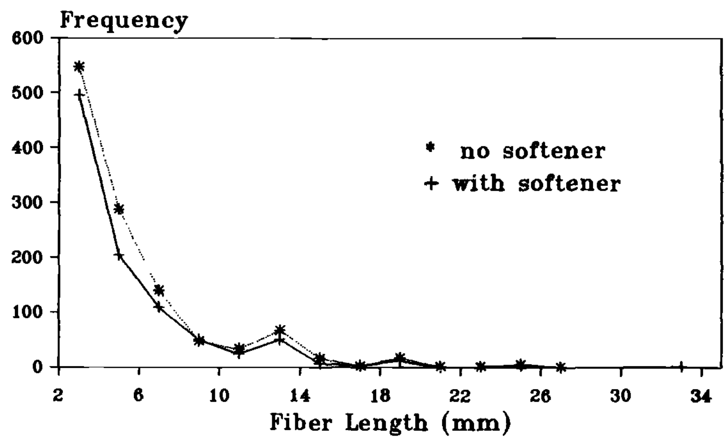

FIG. 6—*Length distribution of fibers ≥2 mm transferred—all MSL fabrics (A, B, C, D, G, and H).*

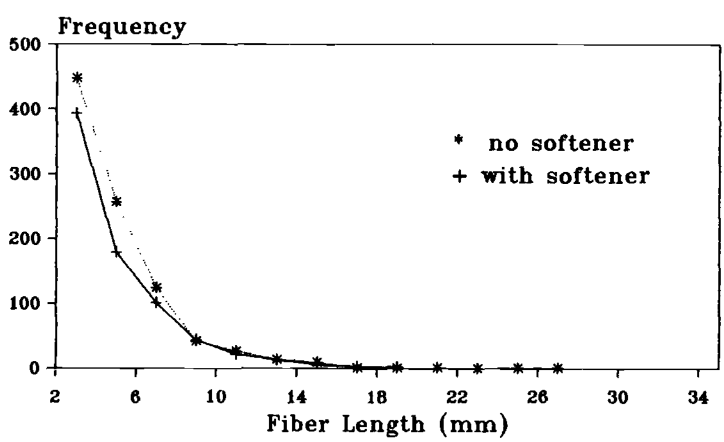

FIG. 7—*Length distribution of fibers ≥2 mm transferred—woven MSL fabrics (A, B, C, and D).*

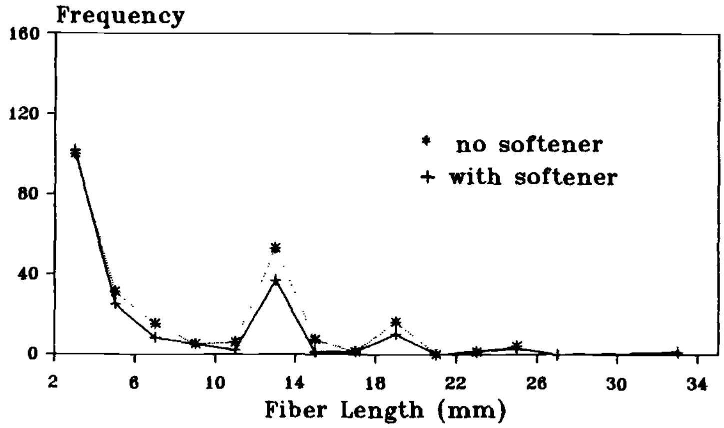

FIG. 8—*Length distribution of fibers ≥2 mm transferred—knit MSL fabrics (G and H).*

from the exponential length decrease and shows increased numbers of fibers at 13, 19, and 25 mm lengths. Figure 7 does not exhibit these increases. The manufacturer of the MSL fibers informed us that the three shortest lengths contained in MSL were exactly 13, 19, and 25 mm. We can conclude from this that significant transfer from knit fabrics probably occurred by disentanglement and release of whole fibers. We also can conclude that this transfer mechanism did not release a significant number of fibers from woven fabrics even though they were manufactured from identical MSL fibers. As stated previously, the distance between yarn interlacings in several woven fabrics was at least as long as those of the knit fabrics, so this factor cannot account for the observed differences in fiber transfer. One possible reason for this difference in fiber transfer might be that knit yarn loops were more easily distorted during abrasion than woven yarn floats, so whole fibers were more accessible from knit fabrics.

Although the frequency distribution of MSL fibers in the fabrics was unknown to us, we know that their number increased as the fiber length increased from 13 to 25 mm. It is important to note that the number of 13, 19, and 25-mm-long transferred fibers decreased rapidly with increasing fiber length. It is significant that, even though the population of fibers in the fabrics increased with increasing fiber length in the 13 to 25-mm range, the number of transferred fibers decreased with increasing length. We may conclude that whole fibers considerably longer than 25 mm would not be likely to transfer.

For the fabrics examined in this study, we may conclude that non-MSL knit fabrics and woven fabrics containing fibers of 38.1 mm length did not transfer a significant number of whole fibers. Transfer from these fabrics must have involved predominantly fiber fracture followed by the release of fiber fragments.

Conclusions

A fiber transfer abrasion tester (FTAT) was used to investigate the influence of fabric softener on fiber transfer from nine medium-weight apparel fabrics. Fabric-on-fabric abrasion was induced to study fabrics rubbing with low pressure and a slow rate for only a brief time. Fiber transfer was evaluated in terms of the total number of fibers transferred, as well as the number, mean length, and length distribution of transferred fibers ≥2 mm long.

The greatest number of fibers were transferred from a twill fabric manufactured from staple fibers, whereas the fewest fibers were transferred from a fabric manufactured from continuous-filament fibers. Fabric softener significantly increased the total number of fibers transferred from most fabrics. Softener had less effect on the number and mean length of transferred fibers ≥2 mm long. Softener generally decreased transfer of fibers at all lengths ≥2 mm. Although fiber denier, fabric weave, knit type, and fabric thread count individually affected transfer, softener did not interact strongly with these structural features.

The dominant mechanism of fiber transfer from all fabrics either with or without softener was fiber fracture. This was true even though the global pressure used to induce transfer was substantially less than the fiber breaking stress. The stress applied during abrasion apparently was localized so that the fiber breaking strength was readily exceeded. When fiber fracture appeared to be the only mechanism by which fibers were transferred, the number of transferred fibers decreased exponentially with increasing length of transferred fibers. Knitted fabrics produced from fibers of multiple staple length (MSL) exhibited significant transfer by the mechanism of disentanglement and release of whole fibers. This mechanism produced marked deviations in the exponential function associated with transfer by only the fracture mechanism. Deviations were most significant for short fiber length groups of the MSL fibers. On the other hand, few fibers from woven fabrics produced from MSL fibers transferred by the mechanism of disentanglement and release of whole fibers.

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References

[*1*] Peterson, J. L., Mihajlovic, S., and Bedrosian, J. L., "The Capabilities, Uses, and Effects of the Nation's Criminalistics Laboratories," *Journal of Forensic Sciences*, Vol. 30, No. 1, Jan. 1985, pp. 10–23.

[*2*] Locard, E., "Dust and Its Analysis," *The Police Journal*, Vol. 1, 1928, pp. 177–192.

[*3*] Pounds, C. A., and Smalldon, K. W., "The Transfer of Fibres Between Clothing Materials During Simulated Contacts and Their Persistence During Wear: Part I—Fibre Transfer," *Journal of the Forensic Science Society*, Vol. 15, 1975, pp. 17–27.

[*4*] Kidd, C. B. M. and Robertson, J., "The Transfer of Textile Fibers During Simulated Contacts," *Journal of the Forensic Science Society*, Vol. 22, 1982, pp. 301–308.

[*5*] Pounds, C. A., and Smalldon, K. W., "The Transfer of Fibres Between Clothing Materials During Simulated Contacts and Their Persistence During Wear: Part III—A Preliminary Investigation of the Mechanisms Involved," *Journal of the Forensic Science Society*, Vol. 15, 1975, pp. 197–207.

[*6*] Bresee, R. R., "Evaluation of Textile Fiber Evidence: A Review," *Journal of Forensic Sciences*, Vol. 32, No. 2, March 1987, pp. 510–521.

[*7*] Robertson, J. and de Gamboa, X. M., "The Transfer of Carpet Fibres to Footwear," Tenth Triennial Conference of the International Association of Forensic Sciences, Oxford, England, Sept. 1984.

[*8*] Parybyk, A. E. and Lokan, R. J., "A Study of the Numerical Distribution of Fibres Transferred from Blended Fabrics," *Journal of the Forensic Science Society*, Vol. 26, No. 1, Jan. 1986, pp. 61–68.

[*9*] Salter, M. T., Cook, R., and Jackson, A. R., "Differential Shedding from Blended Fabrics," *Forensic Science International*, Vol. 33, No. 3, 1987, pp. 155–164.

[*10*] "AATCC Test Method 93–1984, Abrasion Resistance of Fabrics: Accelerotor Method," *AATCC Technical Manual*, Vol. 64, American Association of Textile Chemists and Colorists, Research Triangle Park, NC, 1989.

[*11*] Annis, P. A. and Bresee, R. R., "An Abrasion Machine for Evaluating Single Fiber Transfer," *Textile Research Journal*, Vol. 60, No. 9, Sept. 1990, pp. 541–548.

[*12*] Annis, P. A. and Bresee, R. R., "Abrasion Resistance Using Single Fiber Transfer and Other Abrasion Testers," *Textile Chemist and Colorist*, Vol. 23, No. 2, Feb. 1991, pp. 11–15.

[*13*] Annis, P. A., Bresee, R. R., and Cooper, T. R., "The Influence of Textile Structure on Single Fiber Transfer from Woven Fabrics," *Textile Research Journal*, in press.
[*14*] Rae, A., "Control of Mounting Torque for Specimens in Abrasion Testing," *Journal of the Textile Institute*, Vol. 58, 1967, pp. 139–140.
[*15*] "AATCC Test Method 124–1984, Appearance of Durable Press Fabrics After Repeated Home Laundering: Washing Procedure IV," *AATCC Technical Manual*, Vol. 64, American Association of Textile Chemists and Colorists, Research Triangle Park, NC, 1989.

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