Use of Wavelet Analysis for an Objective Evaluation of the Formation of Pills in Nonwoven Fabrics

Dandan Wang[1], J. R. Barber[2], W. Lu[2] and M. D. Thouless[1,2]

[1] *Department of Materials Science & Engineering*

[2] *Department of Mechanical Engineering*

University of Michigan, Ann Arbor, MI 48109

Abstract

A quantitative technique to measure pill formation on fabrics has been developed using a wavelet analysis. This technique permits the damage of fabrics to be evaluated with a minimum of human interpretation. A two-dimensional, discrete-wavelet transform was applied to images of nonwoven fabrics, and an optimal approach was found by which the background information could be eliminated from the digital data to obtain characteristic information about the pills. This information, corresponding to the degree of damage, is expressed in terms of a gray-value ratio that is extracted from the details of the wavelet characterization. It has been shown that the resultant parameter correlates well with an independent, qualitative assessment of damage.

(December 22, 2017)

(Revised: September 18, 2018)

Key words

Nonwoven Fabric, Objective Evaluation, Pill, Wavelet Analysis

1. Introduction

Over the past 40 years, nonwoven fabrics have become an independent and technically sophisticated portion of the textile industry, playing a leading role in many market segments[1]. The global market for nonwoven fabrics is rapidly growing, worth $47 billion in 2018, up from $33 billion in 2013[2]. The use of non-woven fabrics has increased significantly because they can be produced directly from raw materials, and manufactured in a continuous fashion that avoids complex conventional textile operations such as braiding, weaving or knitting[3-5]. Non-woven fabrics are used as the basis for more than 10 billion disposable diapers sold every year for infants and toddlers. They are also used for other applications including clothing, filtration products, and seat cushions.

During service both knitted and nonwoven fabrics experience fretting and abrasion. This can lead to damage such as "fuzz", in which fiber ends protrude from the surface of a fabric[6,7], and "pills", which are balls of tangled fibers held to the surface of the fabric by one or more fibers[6,7]. This damage is undesirable since it degrades both the appearance and texture of a fabric in consumer applications, as well as reducing the integrity and function in both consumer and industrial applications. The applications for which non-woven fabrics are used can be just as sensitive to concerns about wear from an appearance or texture perspective, as are the applications for which woven fabrics are used.

The development of pill-resistant fabrics for both woven and non-woven fabrics will require a fundamental understanding of the mechanics of wear mechanisms to understand the formation of pills. However, these mechanisms are expected to be somewhat different for woven and non-woven fabrics. For either case, there is a need to develop quantitative methods to evaluate the formation of pills. While such methods have been developed for woven fabrics, these rely on the underlying periodic structure of the woven fabric. Such periodicity does not occur in non-woven fabrics, and the current industry standard of ASTM 4970[8] for evaluating pilling requires the subjective opinion of trained experts. The only other technique that has been described in the literature that could be used to evaluate pilling is to scan the surface of a fabric from point to point using a laser, and to detect the presence of pills from changes in the surface topography[10]. However, this entails the use of expensive equipment, and is not very efficient. In this paper we describe a simple digital-image approach that requires a minimal amount of human intervention, and can be used for evaluating pills in non-woven fabrics.

Digital-image analyses have been explored previously for the purpose of identifying pills[11-22]. However, the inherent challenge with digital-image techniques is developing methods to separate the signals associated with the presence of pills from other confounding signals, such as differences in illumination, unevenness of the fabric surface, and the texture.

One approach is to use a two-dimensional, discrete-Fourier-transform method[12,13] to separate the periodic structure of woven and knitted fabrics from the non-periodic structure of pills. However, this technique can only give frequency information over the entire domain, so if, for example, small perturbations or localized features exist, such as isolated pills, they may be missed because the signal is diluted during the transform procedure (Figure A1). Furthermore, the method does not give any information about the location of pills. It can only identify whether there are pills in the domain. Finally, it relies on a distinction between the periodic structure of a woven fabric, and the non-periodic structure of pills. Therefore, it cannot be used for identifying pills in non-woven fabrics.

To capture localized data in both the frequency and spatial domains, wavelet analyses have been used, mainly for woven or knitted fabrics[9, 11, 14-22]. One advantage of these techniques is that frequency information is not lost during the inverse transformation. The technique works by describing the digital image in terms of shifted and scaled versions of finite-length or fast-decaying oscillating waveforms called "mother wavelets." Selections of data are compared to the wavelets, producing coefficients that evaluate the degree of matching between the data and wavelets. The presence of a disturbance at a suitable scale, such as a pill, can then be identified.

In previous work, the standard deviation of the matching coefficients for scales that corresponded to the periodic pitch of the fabric was used to quantify the degree of damage. The concept behind this approach is that if data with the periodicity of original pattern are compared to the wavelet, the coefficients will be similar. Therefore, the standard deviation of these coefficients should be relatively small for images of undamaged fabrics. Conversely, if there is a pill on the surface of the fabric, the standard deviation of the coefficients should increase since any pills will disrupt the underlying periodicity of the fabric.

The approach described above relies on the presence of a periodic structure, which may not be present in a nonwoven fabric. By contrast, the technique described in this paper focuses on capturing the pill information directly, rather than the modification of a periodic texture. Although the fabrics used in this study do actually have an underlying pattern associated with the array of bonding pins, this pattern is not used in the analysis. The present approach focuses on an analysis at the scale of the pills that are to be described. So, the analysis is performed at the specific scale associated with the pills, and the signals associated with other scales are removed. This concept is used to develop a parameter based on a wavelet analysis that provides an objective assessment for the degree of damage.

2. Reconstruction of pill information

Figure 1(A) shows an optical image of a nonwoven fabric before abrasion. The hexagonal close-packed pattern of spots that can be seen is the result of the hot pressing process used to bond the fibers together. Figure 1(B) shows an optical image of a similar piece of fabric with a number of pills that formed after abrasion. Although the pills are clearly visible to an observer, it is not obvious how to describe the extent of pilling in a non-subjective fashion. A quantifiable method to describe the pilling, in a fashion that is independent of the perceptions of an observer, was the goal of this study.

A wavelet analysis involves correlating a single waveform of a given wavelength, known as the "mother wavelet." with the digital signal of interest. In a fashion similar to Fourier analysis, wavelet analysis involves decomposing the original signal into shifted and scaled forms of the mother wavelet[22]. The process starts with the finest scale of wavelet, and the correlated portion is subtracted from the original signal. The image recreated from the subtracted portion of this first step is referred to as "level 1" in the images that follow. The remnant signal is then operated upon by a wavelet with twice the wavelength of the previous one, and the image recreated from this second signal is referred to as "level 2." This process is repeated until the wavelength of the wavelet applied to the remaining signal is much coarser than any scale of interest. In the present case, seven frequency scales were used, with the finest corresponding to 1/256th of the image length, and the coarsest level corresponding to a quarter of the image length.

The process of correlation and subtraction filters the signal into components that incorporate information about features with characteristic sizes. The effect of this digital manipulation on the image of an abraded sample shown in Fig 1(B) is illustrated in Fig. 2. This figure shows a sequence of images resulting from a wavelet analysis from the final coarse levels (low frequency) to the initial fine levels (high frequency). The specific form of the wavelet used to generate these images is shown in Fig. 3. However, it is important to appreciate that the results do not depend on the precise shape of the wavelet chosen.

The major issue of this technique that needs to be addressed is how to determine the level or combination of levels that best characterizes the features of interest, without excessive contamination from other features. This is the only step of the process in which some human intervention is required: determining the appropriate scale of the features. However, once this is decided, the process proceeds by recognizing that each level of wavelet detects features with dimensions that approximately match their wavelengths (Figure A3). If the N^{th} level of wavelets is defined to have a wavelength of 2^N pixels, the image of features that can be detected by this level of wavelet is also 2^N pixels. Likewise, if the size of shifted and scaled versions of the wavelet matches the size of a pill, the pill information will be picked up by returning a large wavelet coefficient. For example, consider a case in which the physical size of the portion of the fabric contributing to an image is $a \times a$ mm^2, the digital size of the corresponding image is $m \times m$ pixels^2, and the features of interest have a physical size of d mm. Since the features of interest in this case are captured by $m \times d/a$ pixels in the image, a wavelet level of N_c, given by

$$N_c = \log_2\left(\frac{md}{a}\right) \qquad (1)$$

will return coefficients whose magnitudes reflect the density of features at this size scale.

For the specific sample considered in this paper, the pills that form in the fabric are in the range of 2.5 mm to 5 mm. The images of the fabric were cropped to a size of 512 × 512 pixels^2. This was found to provide a satisfactory level of resolution, and amenable to a wavelet analysis. The microscope was calibrated so that a digital image of this size image corresponded to a physical domain of 40×40 mm^2. Therefore, using Eqn. (1), a level of $N=5$ detects features of about 2.5 mm, and a level of $N = 6$ detects features of about 5 mm.

After the wavelet coefficients at these two levels (N= 5, 6) were determined, the coefficients at the other levels were discarded. The chosen coefficients were used to synthesize a new image matrix by an inverse wavelet transform. A visualization of the synthesized image matrix is shown in Fig. 4(B), and compared to the original unfiltered image, Fig. 4(A). Notice that the reconstructed image broadly captures the morphology of the pills.

The coefficients corresponding to the wavelets at levels 5 and 6 increase in magnitude with an increasing number of pills on a given area of fabric. This motivated the use of a parameter P, defined as the sum of all positive elements in the coefficient matrix of the synthesized image divided by the total number of the elements in that matrix. It will be shown that this parameter correlates with the extent of damage, in the form of pills, after an abrasion test.

In order to further compare the fabric before and after abrasion, P was normalized by its initial value, P_o, obtained from an unworn fabric that would usually be available as a reference sample. This normalized quantity is identified as the "gray-value ratio":

$$\delta = \frac{P}{P_o} \quad . \qquad (2)$$

It is the gray-value ratio, δ, that is used to provide a quantitative measure of the damage.

3. Experimental methods

The hardware used included an optical microscope, a light source consisting of a light-emitting diode, a digital camera, and a computer (Fig A4). The magnification of the microscope and the resolution of the camera were matched by a one-time calibration process to ensure that a 40×40 mm^2 area corresponded to a 512×512 $pixels^2$ image.

The analysis was developed using the computer program Matlab®. First, the image was cropped to a size of 512×512 $pixels^2$, so that it corresponded to the correct area. The image was converted to a gray-scale. As described above, it was determined that the coefficients at the fifth and sixth level would correspond to the length scales associated with the pills of interest. Then, the coefficients at these levels were extracted by a multilevel, 2-D, wavelet-decomposition, and an image containing only the information at these two levels was reconstructed by an inverse wavelet-transform. Finally, P was obtained, and a similar process was used to obtain P_o from an undamaged sample, so that the corresponding gray-value ratios could be calculated.

This technique was used on several different surfaces to explore whether it could discriminate between subtle gradations of surfaces that were all nominally white, but clearly had different appearances. Once the discriminatory ability of the technique had been verified, it was applied to micrographs of fabrics that had been worn to different degrees, and compared the ratings we obtained with those of an independent, qualitative evaluation based on ASTM 4970[8].

4. Results

The gray value, P, for a pure digital white image that is absolutely uniform, should be zero. However, as shown in Fig. 5, even nominally untextured surfaces do not have gray values of zero. The gray value contains information about non-uniformities in the image corresponding to the wavelengths of level 5 and level 6. It is interesting that the gray value appears to scale systematically with what an observer might qualitatively describe as a departure from uniformity in the image. In particular, this figure emphasizes the need to normalize gray values by a reference value. In the case of damaged fabrics, the reference value of P used is that of a nominally undamaged fabric, P_o.

In order to compare our gray-value-ratio rating to a traditional, qualitative rating method[20], the degree of damage on five non-woven fabrics was evaluated by both methods. Fabric samples were abraded on a Martindale abrasion tester by an independent employee at Procter & Gamble, who also read the worn samples using the traditional rating method. For this procedure, the bottom of the non-woven samples was clamped onto a felt layer, and a rubber-covered footer on the top abraded the samples following a

Lissajous curve. The resulting damage was then rated by comparing the damage with standard images from 1 (no pilling) to 5 (extreme pilling and destruction of sample). The worn samples were then supplied to the University of Michigan, and evaluated independently by the wavelet analysis described here.

The images were obtained and analyzed as described above, and the results compared with the traditional "Martindale Rating" methods in Fig. 6. This figure shows that there is excellent consistency between the two methods. The correlation coefficient between the subjective results and the results obtained by the wavelet technique was 0.9025. In conclusion, the technique we have developed not only requires only a limited amount of human interpretation, but also agrees well with the traditional rating method.

5. Discussion

Two factors that might influence the quantification of wear were also considered: the choice of the mother wavelet, and the rotation of the samples during imaging.

To investigate the potential effect of using different forms of wavelet, a range of different wavelets (Fig. 7) were used to test whether there was any difference in the resultant quantification. The six wavelets chosen came predominately from two wavelet families: Daubechies and Coiflets[24]. The reason for choosing these wavelets was that they are compactly supported and orthonormal, which makes discrete wavelet-analyses practicable[9, 22, 23-25]. In addition, other studies have chosen one of these wavelets because they can successfully match the main features of woven fabric textures[14, 19, 20]. The different mother wavelets that we used to detect features of the same size range are shown in Fig. 7. Similar results were obtained with all forms of the mother wavelets tested (Figure A5). The difference in gray-value ratios obtained from all the mother wavelets was only around 4%. Therefore, the choice of wavelet is not critical when investigating pilling in nonwoven fabrics.

Rotation of the sample should only affect the resulting measurements if the fabric possesses significant anisotropy. Although the periodic structure of nonwoven fabrics is not as obvious as that of woven fabrics, the hexagonal array of the bonding pattern and the manufacturing orientation during fiber lay-down resulted in a certain degree of anisotropy. Also, orientation effects might be introduced by the direction of sliding during abrasion. In order to study this possible effect of anisotropy, we introduced a deliberate rotation into the samples before quantifying the damage. We found that the effect of rotation on the measured gray-value ratio was no more than 6% (Figure A6). This lies well within other effects of experimental variability shown in Fig. 6.

6. Conclusions

A pill-level technique using two-dimensional, discrete-wavelet transforms has been reported to provide an objective measure of pilling for nonwoven fabrics. It has been shown that this approach using the gray-value ratio to quantify pilling correlates very well with a traditional subjective approach. Since the approach we have developed requires minimal human interpretation (human interpretation is needed only during the initial calibration for a specific type of fabric and abrasion conditions), it is expected that it can form the basis for an automated, integrated and efficient system for evaluation of fabrics within industrial contexts. In addition, it will allow a quantitative description of pilling that can be used for developing wear models.

This method was developed for non-woven fabrics, which lack an underlying periodicity that can be affected by the formation of pills. The loss of periodicity can be used to detect damage in woven fabrics, so the present technique may not be needed for such fabrics. However, it should be noted that the technique could be used for woven fabrics, provided the pills have a scale that can be separated from any underlying scale of the weave pattern. For example, by applying the technique to published images of pills in a knitted fabric[17], it was possible to show that the damage could be quantified by this approach.

Acknowledgements

The authors are grateful for financial support from The Procter and Gamble Company, and for allowing them to use the data of Fig. 6. The authors also acknowledge many useful discussions with Dr. R. Hamm and Mr. O. Isele.

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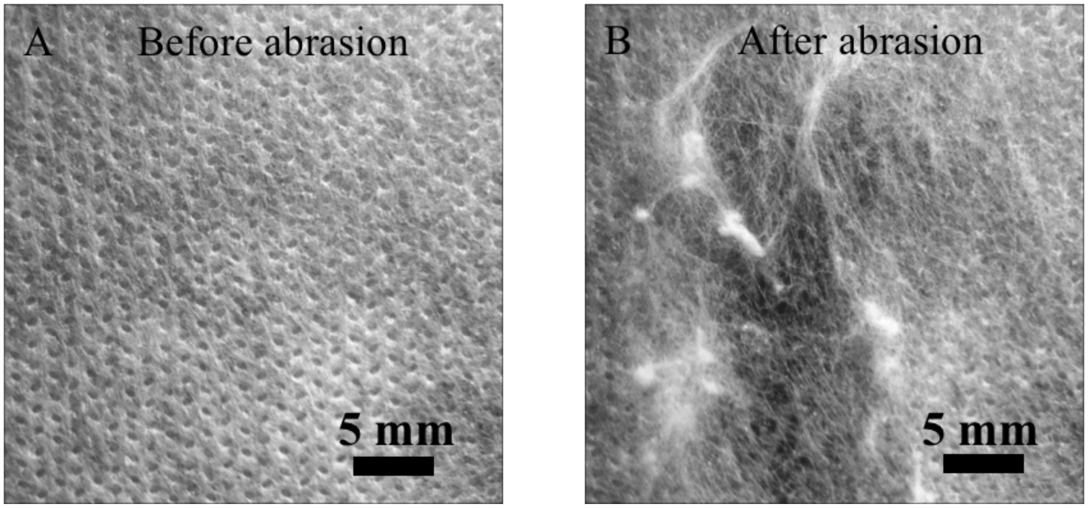


Figure 1. (A) Image of fabric before abrasion. The periodic structure that can be observed in this image results from the thermal bonding sites. **(B)** Image of fabric after abrasion, showing the presence of pills of few millimeters in length. It is these features that our technique focuses on, not the loss of periodicity at the smaller scale.

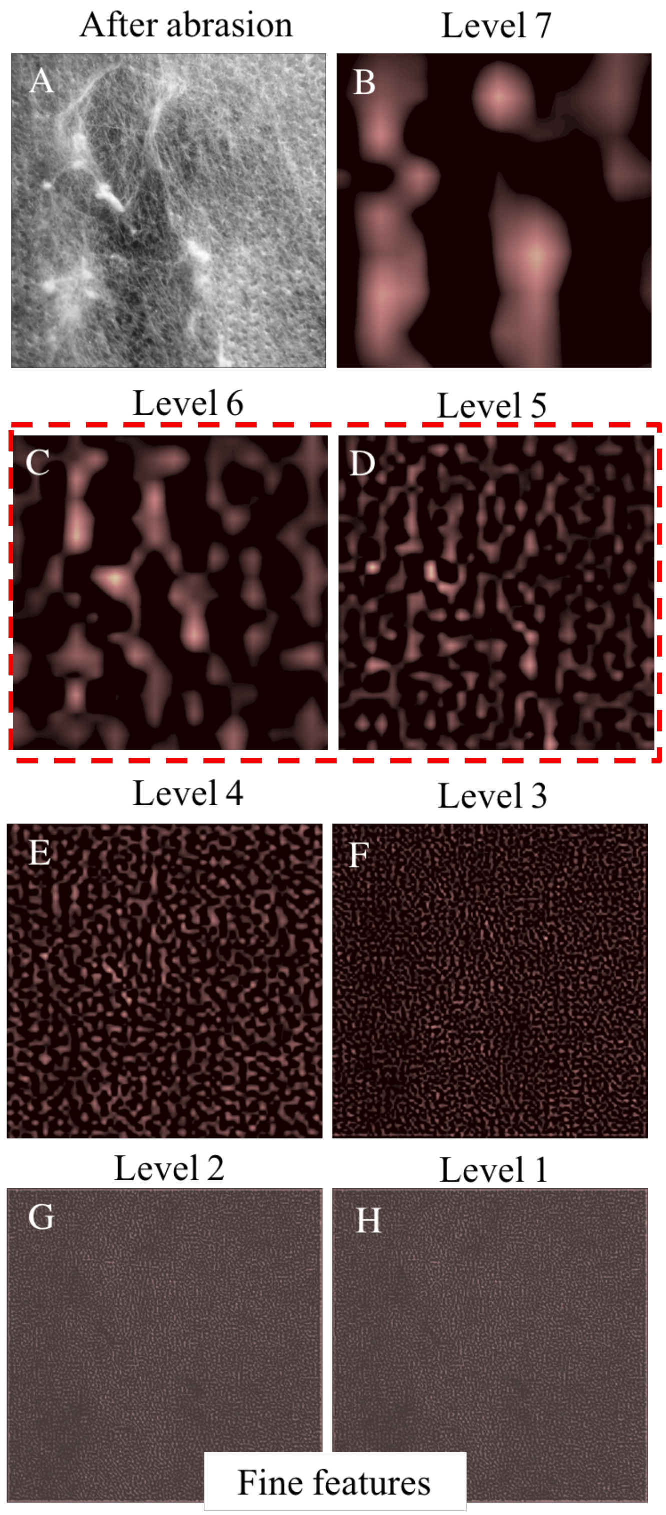


Figure 2. **(A)** Image of non-woven fabric after abrasion; **(B-H)** Decomposition of the original image after subtraction of the digital information at increasingly fine scales.

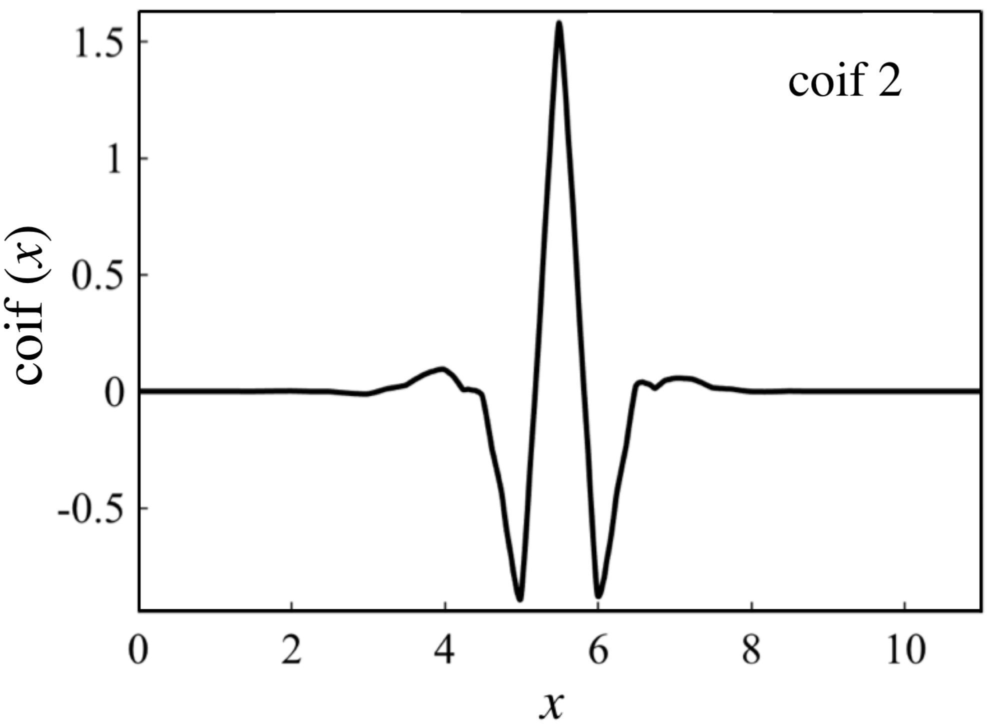


Figure 3. The mother wavelet used to create the images of Figure 2.

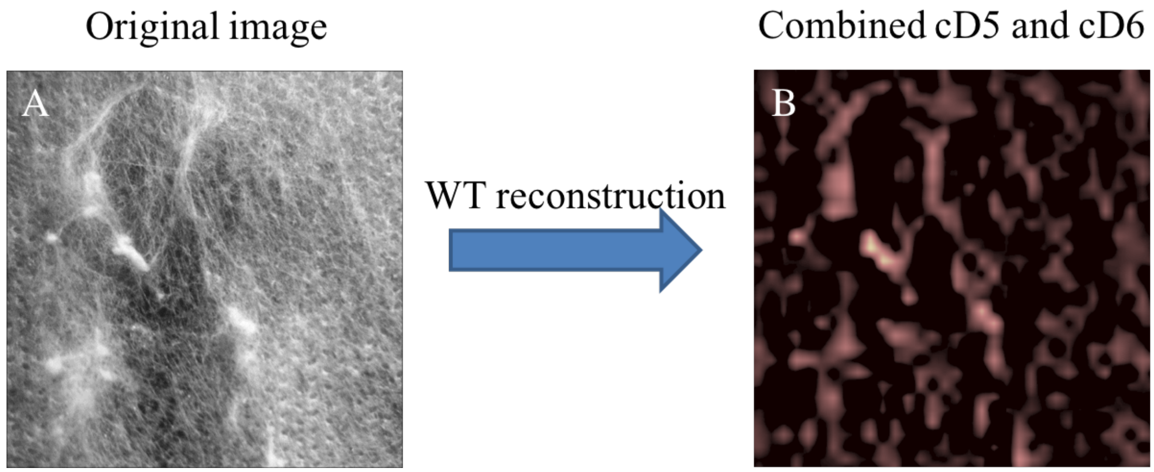


Figure 4. Reconstruction of the signals corresponding to levels 5 and 6 results in the image on the right **(B)**. This can be compared to the unfiltered image of the abraded specimen on the left **(A)** to show that this reconstructed image broadly captures the pills.

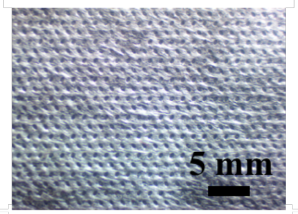
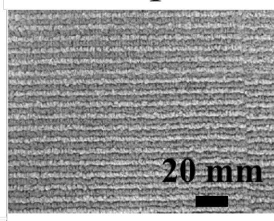
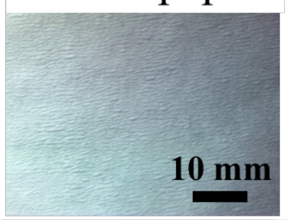
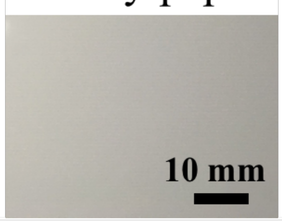
Surface	Gray value
Fabric 	2.9±0.3
Carpet 	2.4±0.4
Tissue paper 	1.3±0.1
Glossy paper 	0.14±0.02
Pure digital white image	0

Figure 5. Gray value, *P*, of a pure digital, white image, paper-based materials, and fiber-based materials.

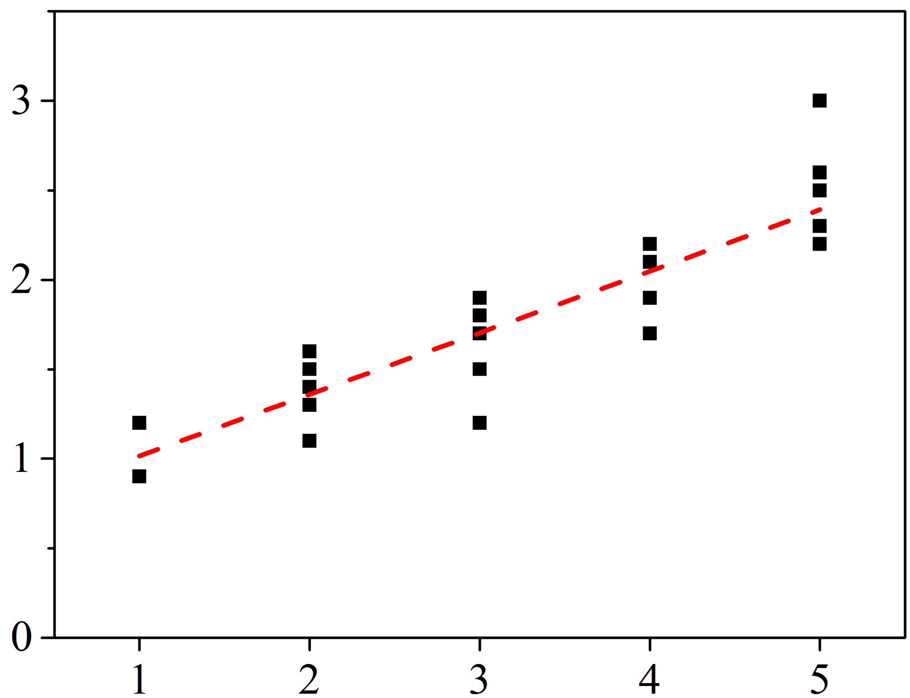


Figure 6. The measured gray-value ratio, δ, correlates well with a traditional rating method. (Independent measurements, the "traditional ratings" are courtesy of P&G.)

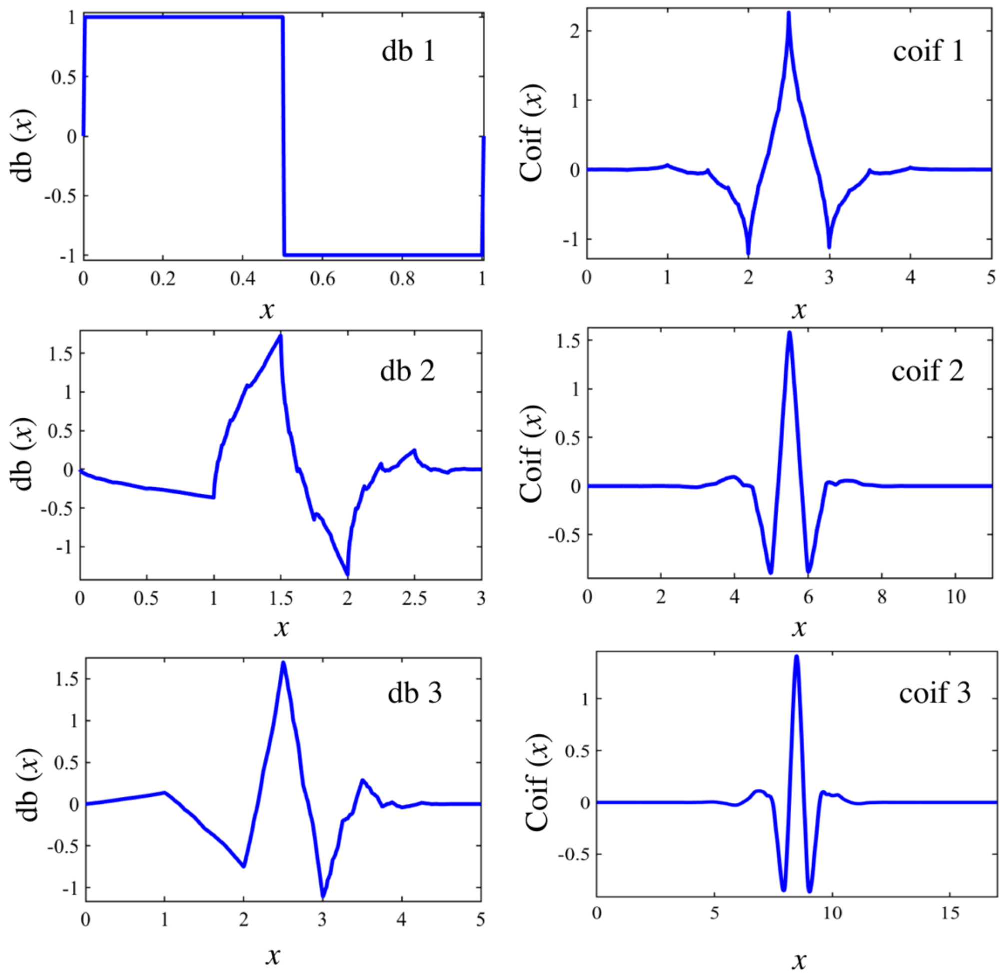


Figure 7. Six different mother wavelets used to study the effect of the choice of wavelet.

Appendix: supporting information

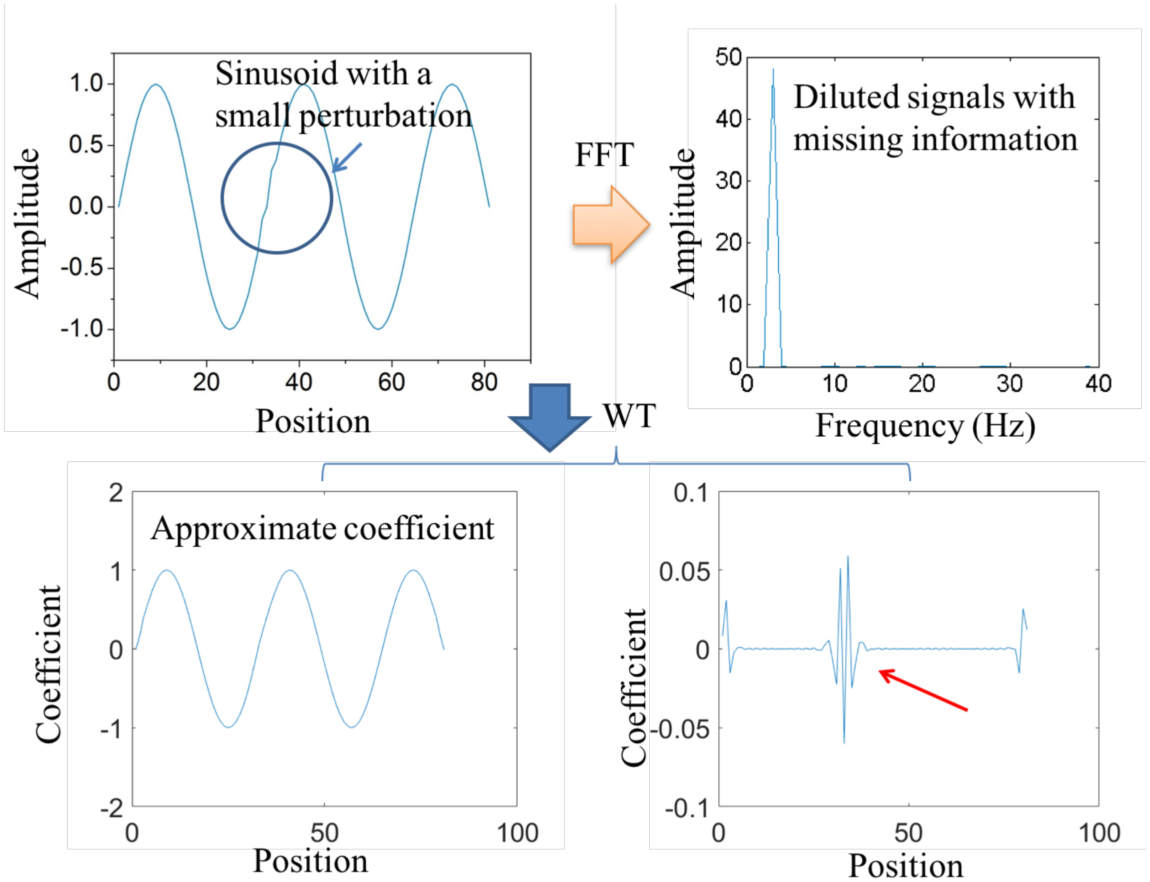


Figure A1. Illustration of the difference between a two-dimensional, discrete-Fourier-transform and a two-dimensional, discrete-wavelet transform based on a sinusoid with a small perturbation. The limitation for two-dimensional, discrete-Fourier-transforms is that, since the signal is diluted during the transform, small perturbations or localized features may be missed. In order to capture localized data in both the frequency and spatial domains, a wavelet analysis has been introduced to analyze digital images of fabrics.

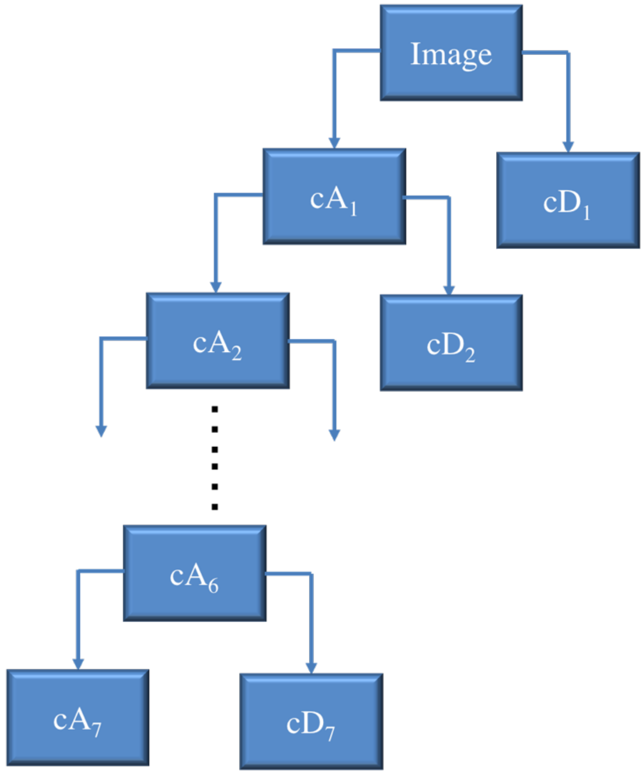


Figure A2. This figure illustrates the algorithm for a wavelet analysis. It shows the decomposition of an image into seven levels. At each level, the approximate sub-image is decomposed into the high-frequency components (cD_i) that is subtracted from the original signal to leave the remnant consisting of lower-frequency components (cA_i)

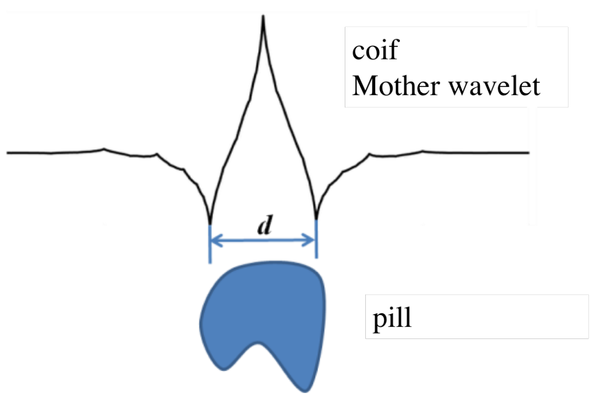


Figure A3. Relation between the size of wavelet and the size of pill. If the size of the shifted and scaled version of the wavelet matches the size of pill, the pill information will be picked up by returning a large coefficient.

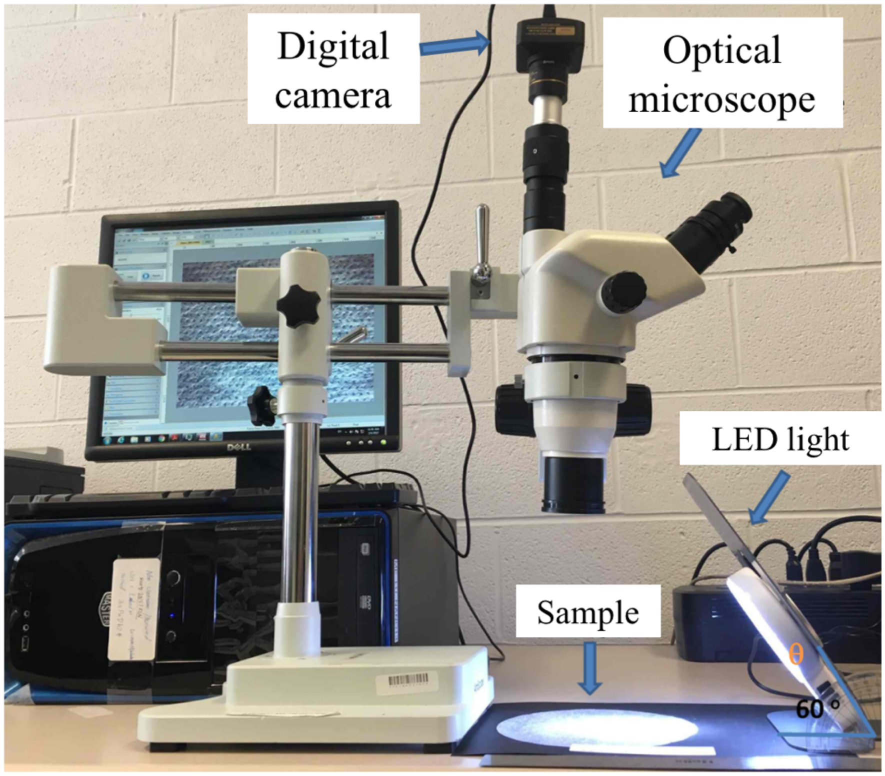


Figure A4. Hardware set-up for wavelet analysis. The hardware set-up was composed of an optical microscope, an LED light, a digital camera, and a computer. The magnification of the microscope and the resolution of the camera was matched by a one-time calibration process as described in Section 2. The appropriate magnification of the microscope and camera resolution was such that the region of interest can be imaged to a size of 512 by 512 pixels or larger. This required a digital camera with a resolution of 0.3 M pixels or higher.

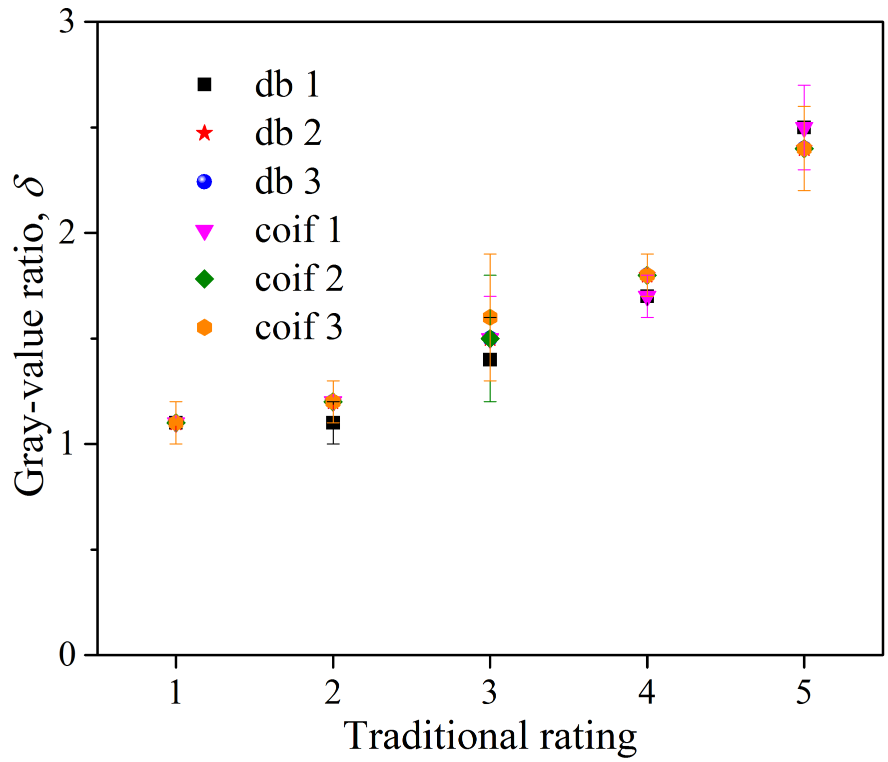


Figure A5. In order to further optimize the wavelet analysis for a non-woven fabric, a range of candidate wavelets were used to test the influence of different mother wavelets. The six wavelets chosen were from two wavelet families: Daubechies and Coiflets (see Fig. 7 in the main text for the key to the shapes of the wavelets). The samples from the five groups analyzed in Fig. 6 were used for this analysis. The error bars represent one standard deviation for the results from the different samples. The plot shows that the choice of mother wavelet has a negligible effect on the choice of wavelet.

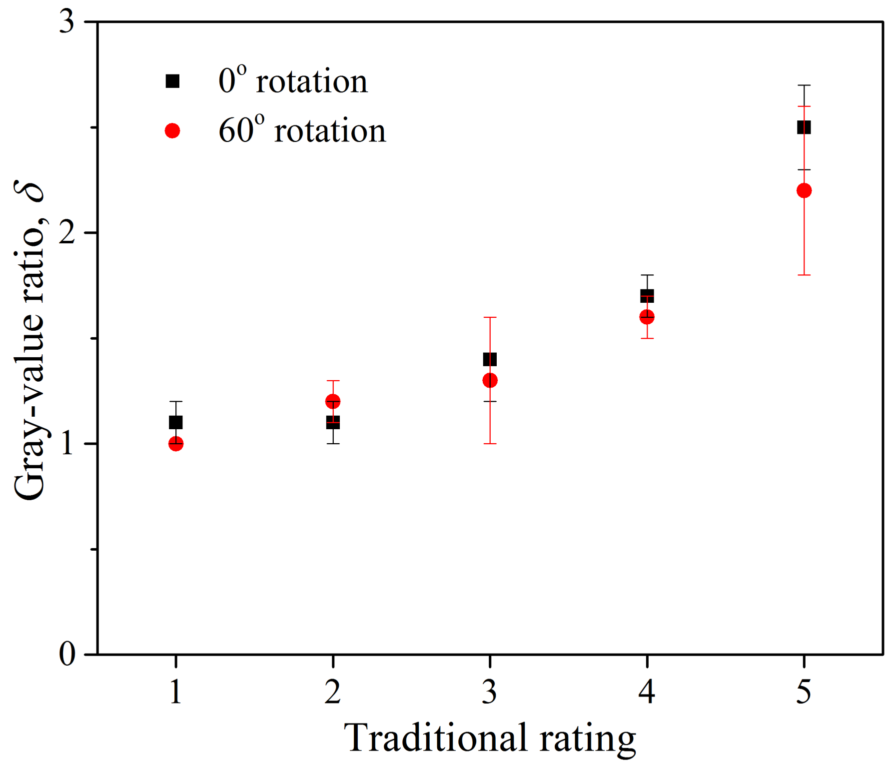


Figure A6. Rotation of the fabric had negligible effect on the analysis method. A non-woven does not have as obvious a periodic structure as a woven fabric does. However, for the non-woven fabric in the present studies, there were several factors that could lead to anisotropy. The first was the bonding pattern, which had a hexagonal close packing form. The second was the production orientation, which was along the close packed direction of the bond sites. The third was the wear direction. Despite these effects, the difference of degree of damage before and after rotation was only around 6%. The error bars represent one standard deviation in the variation for the five different specimens analyzed from each of the sets of samples used to obtain the data of Fig. 6.

In order to study further how rotation might influence the results, a second experiment was conducted. This experiment involved taking two sheets of white paper, drawing a line in the center of one sheet, and drawing a solid circle in the center of the other sheet. These sheets of paper were rotated through 0^o, 30^o, 60^o, 90^o, 120^o, 150^o, and 180^o. For the paper with a line, the image was different upon rotation, while the image was invariant for the circle. The difference in gray value for both paper with line and paper with circle before and after rotation was small, also about 4%.