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Optical 3D-system for fabric pilling assessment: A complementary tool to avoid evaluation errors

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ABSTRACT

Pilling is a defect that affects the appearance of fabrics, being its assessment carried out by the textile sector using a subjective method (reference). This method is simple and works well in most cases. However, uncertainties may arise when complicated cases are under evaluation. The current study addresses the use of an optical 3D-system for the topographic surface reconstruction of fabrics for their objective assessment. With the topographic data of the fabrics, it was calculated the total volume of pilling formed in their surfaces. Their equivalent pilling grades were also achieved through use of a correspondence model. A results comparison was then carried out with both methodologies (3D-system and subjective), which made possible to identify cases of analysis where the grading attributed to the fabrics did not match. These cases were thoroughly analyzed, and it was found that one of the studied fabrics seems to have been over-estimated whereas one other seems to have been under-estimated when initially graded with the subjective methodology.

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Fabrics; pilling assessment; subjective method; optical 3D-system; surface reconstruction

Introduction

Pilling is a surface change that occurs on fabrics resulting from abrasion and wear (Binjie & Hu, 2008). Pilling can be characterized as small balls adherent to the surface of the fabrics due to the entanglement of fiber ends (Araújo & Castro, 1987). It is an inevitable effect because clothes and fabrics are constantly submitted to friction caused by the contact and movement against other surfaces. In some cases, pilling can be very noticeable affecting the surface of clothing severely making them to look unpleasant and unappealing (Cooke, 1985; Kayseri & Kirtay, 2015). For this reason, the proper evaluation and characterization of fabrics to know how they will behave in terms of quality and appearance when used in daily life, is a topic of high interest and relevance for the textile industry and for clothing makers.

For the pilling evaluation, the textile sector uses, as a reference, a subjective evaluation methodology performed by a panel of experts, that consists on a comparison of the fabrics appearance, after being submitted to an abrasion process, with sets of photographic standards (Binjie & Hu, 2008). A grade of pilling is then attributed to the analyzed fabrics ranging from grade 1 (high pilling formation) to grade 5 (no pilling formation) (Binjie & Hu, 2008). This method has the advantage of being simple and easy to perform not requiring expensive equipment. However, due to the subjective nature of the method, grading errors may occur.

As an attempt to overcome the subjectivity of the reference method for the pilling evaluation, several objective methodologies were developed and have been explored by different researchers in the last decades, of which we indicate a few of the conducted studies (Amirbayat & Alagha, 1994; Behera & Mohan, 2005; Chen & Huang, 2004; Eldessouki et al., 2014; Eldessouki & Hassan, 2015; Guan et al., 2017; Hsi et al., 1998; Jasinska & Stempien, 2014; Kim & Kang, 2005; Konda et al., 1990; Mayekar & Nachane, 2016; Palmer & Wang, 2003; Ramgulam et al., 1993; Technikova et al., 2017; Telli, 2019; Xu, 1997; Xin et al., 2002; Yang et al., 2019; Zhang et al., 2009). For instance, Konda et al. (1990) used a computer system with a video camera and a light source for the image acquisition of pilling samples. The authors Rangulam et al. (1993), and Amirbayat and Alagha (1994) made use of a laser triangulation system, and Chen and Huang (2004) used a light projection system for the data capture. For the processing of the pilling data, several different computing approaches were also explored. For instance, Xu (1997) made use of the fast Fourier transform method, Xin et al. (2002) used the two-dimensional Gaussian fit theory for pilling template matching, and Yang et al. (2019) used neural networks. Despite the existent differences in terms of principles/techniques associated to each methodology, in general, they all consist in the acquisition of pilling data, and then in the extraction and calculation of several pilling features enabling

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Table 1. Properties of the four studied fabrics *FA*, *FB*, *FC* and *FD*.

Fabric	Type color	Composition (%)	Weight (g/m^2)	Density of yarns		Count of yarns		Thickness (mm)
				Ends per cm	Picks per cm	Warp (Tex)	Weft (Tex)	
FA	Woven Black	Wool 80 Polyamide 20	245.6	14.0	12.0	83.3 × 1	83.3 × 1	0.723
FB	Woven Dark orange	Wool 80 Polyamide 20	203.9	16.0	14.3	58.8 × 1	58.8 × 1	0.719
FC	Woven Blended brown	Wool 100	231.6	25.0	23.3	19.2 × 2	45.5 × 1	0.524
FD	Woven Pattern with colored yarns	Wool 80 Polyester 20	288.5	10.0	8.0	66.7 × 2 142.9 × 1	66.7 × 2 142.9 × 1	0.881

the achievement of an objective quantification of the pilling formation comparable with the subjective grading.

Due to the importance of this thematic and the strong link that our research group has with the textile sector, this topic has always been a point of interest. In such way, in order to make a contribution in this field exploring different evaluation concepts and points of view, an optical 3D-system, based on optical triangulation, was developed by our research group for evaluation of the pilling formation, and also for evaluation of other manifestations that occur on the surface of the fabrics (Lucas et al., 2010; Mendes et al., 2006; Mendes et al., 2009; Mendes et al., 2010a; Mendes et al., 2010b; Mendes et al., 2011; Mendes et al., 2019).

Regarding the pilling formation, which is the main concern of this work, several pilling coefficients were previously evaluated and compared with the subjective grades of a set of forty-six fabrics of different characteristics (Mendes et al., 2009). It was found that the total volume of pilling was the coefficient most trustful and in better accordance with the subjective methodology (Mendes et al., 2009). Based on the total volume of pilling of the fabrics and on their subjective grades, a correspondence model was created, consisting in the identification and definition of the transition values associated to each pilling grade. A discretized scale was then defined and by simply knowing the total volume of pilling of a given fabric, its equivalent pilling grade in the subjective scale can automatically be attributed (Mendes et al., 2010b). This model was tested and allowed to detect cases on which the subjective evaluations were not in agreement with the appearance of the fabric's surfaces (Mendes et al., 2010b).

In this work, our purpose is precisely to demonstrate that the developed optical 3D-system is a very useful complementary tool to avoid evaluation errors that might be committed in the grading of the fabrics through the subjective method. In particular, this study is focused on the grading comparisons using the reference method and the created correspondence model on four specific cases of interest, on which great differences can be seen between them. The reconstructed 3D images of the fabrics, which show the amount of pilling formed on their surfaces, are presented throughout this work to assist the analysis of the presented cases, allowing the reader to observe exactly what is the appearance of each fabric and relate the 3D images that were reconstructed with the corresponding numerical pilling grades of the fabrics.

Materials and methods

Four different fabrics, identified as *FA*, *FB*, *FC* and *FD*, were selected in this work as our cases of study. The main properties of the fabrics can be consulted in Table 1. Each one of them is composed by a set of four abraded samples prepared using the Martindale Tester. The initial subjective evaluation of the fabrics was performed by a total of 3 experienced evaluators using the standard method TM196 of the Woolmark Company. The selection of these fabrics in particular was related with the initial subjective grades attributed to them and also because of their different appearances. Namely, the fabrics *FA* and *FB*, which are very different comparatively to one another, were both subjectively evaluated as having high pilling formation (grade 1). The other two fabrics, *FC* and *FD*, also very different comparatively to one another, were subjectively evaluated as having mild pilling formation, grade 2-3 in both cases (between grade 2 and grade 3).

In terms of methods, has already mentioned before, an optical 3D-system was used to scan the fabric samples. In the universe of 3D systems, many different approaches are possible and can be considered when designing a customized system. Several examples of 3D scanning technologies applied for inspection of textile surfaces are presented in the work of Montilla et al. (2014). In our particular case, three main characteristics define the optical 3D-system that was developed: 1) white light was used instead of monochromatic laser light for elimination of speckle and to maximize light detection; 2) two image detectors were used for the image data acquisition instead of only one for a more genuine reconstruction process; 3) the system was assembled inside a dark chamber to capture the image data in a total dark environment for elimination of reflections resulting from other sources (Mendes et al., 2006; Mendes et al., 2010a; Mendes et al., 2011).

In terms of operation, the 3D-system works by projecting a thin light stripe onto the surface of a fabric and if pills are present on it, the light stripe will suffer deviations. During the scanning process, images of the light stripe are captured while the fabric moves relatively to it registering a given number of profiles across the extension of the fabric in analysis. For each profile, two images are captured from two different positions, one from the left and the other from the right, as shown in Figure 1. A general view of the system is also shown in Figure 2, where the main elements that compose the system can easily be identified. All the obtained profiles in the scanning step are then processed to determine the corresponding z-values giving rise to a reconstructed 3D image containing the topographic data of the analyzed fabric (Mendes et al., 2010a).

The operation settings used by the optical 3D-system for analysis of the fabrics are the following: triangulation angles $\theta = 45°$; light stripe width = [0.2, 0.3] mm; number of

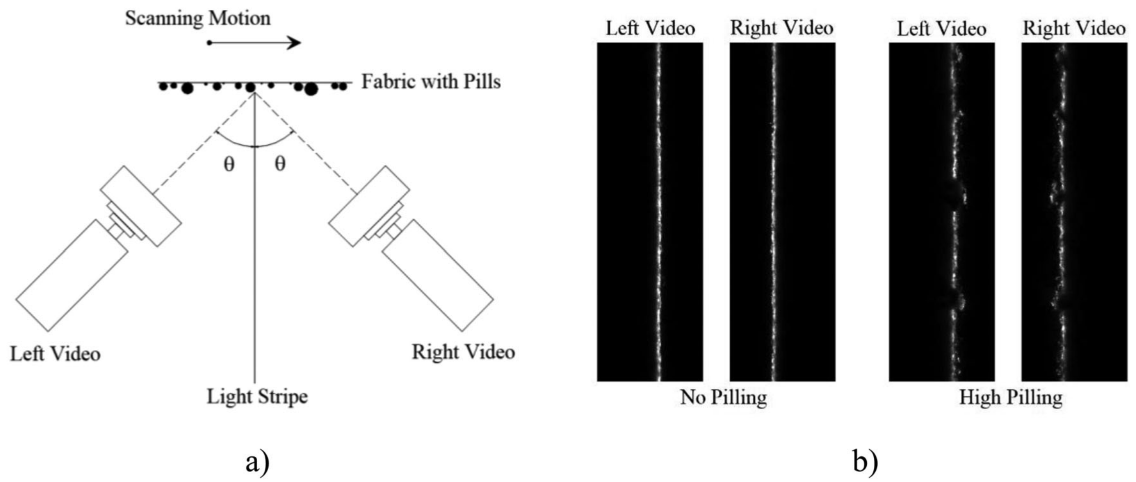

Figure 1. (a) Schematization of the implemented optical 3D-system. (b) Pair of captured images of the light stripe illuminating fabrics with no pilling and high pilling.

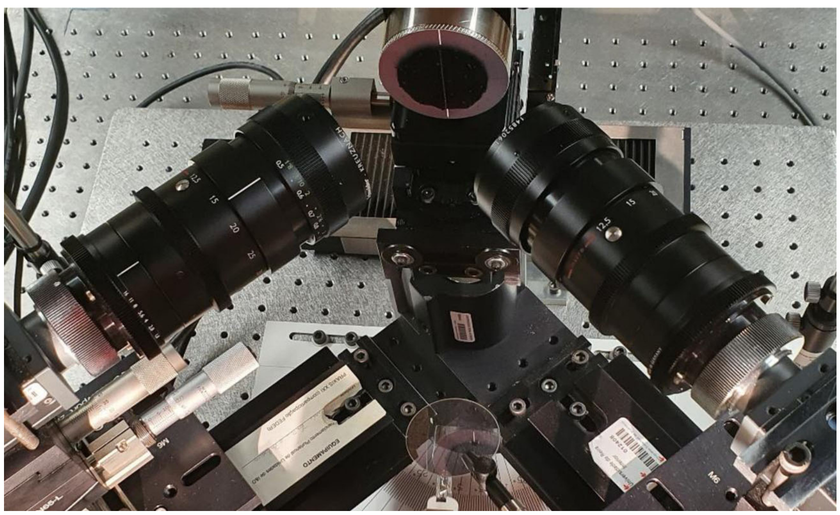

Figure 2. General view of the developed optical 3D-system (the dark chamber was temporarily removed to take the photo with ambient lighting).

profiles = 239; scanning area (horizontal "x "and vertical "y "directions) $= 30 \times 30\,\text{mm}^2$; and a depth resolution of $z_{res} = 44.2\,\mu\text{m}$ (Mendes et al., 2010a; Mendes et al., 2011).

All the procedures for the samples scanning, and for image acquisition, storage and processing were carried out through a software application implemented using the MATLAB® programing language and the Toolboxes for Image Acquisition and Image Processing. This application was also used for the reconstruction and visualization of the 3D images of the samples, and also for the calculations of the total volume of pilling and the corresponding pilling grades. Regarding the pills exhibited on the surfaces of the fabrics, they were isolated through the developed application by subtracting the background level of each abraded sample to their corresponding surface data, and applying a series of filters for noise removal. Then, the total volume of pilling of the fabrics was calculated by simply adding all the pill elements present in the surface of the samples, expressed by the mean and standard deviation of the four abraded samples (Mendes et al., 2009; Mendes et al., 2010b).

Concerning the experimental work conducted in the current study, a comparison of the subjective grades of the fabrics was carried out with the results obtained with the presented optical 3D-system. Specifically, the total volume of pilling was calculated for each fabric as well as the equivalent pilling grade using the created correspondence model, according to the establishments defined in previous works (Mendes et al., 2009; Mendes et al., 2010b).

The reconstructed 3D images obtained for the four abraded samples of each fabric are also presented, from a top view and a perspective view, for a visual inspection of the amount of pilling exhibited on their surfaces. These two views together, are important to properly assess each fabric in terms of pilling. The colormap used for representation of the reconstructed 3D images also makes the image analysis easier. In particular, the used colormap corresponds to a red gradient being very useful to identify topographic changes (pills) in the surface of the samples. Darker areas on the 3D images indicate lower z-values whereas lighter areas on the 3D images indicate higher z-values.

Results and discussion

This section presents the major findings that were obtained for each one of the analyzed fabrics. In particular, Table 2

Table 2. Subjective grade, total volume of pilling, pilling grade based on the correspondence model and grade difference for the fabrics *FA*, *FB*, *FC* and *FB*.

Fabric identification	Subjective grade (*SG*)	Total volume mm^3 (*TV*)	Correspondence model (*CM*)	Grade difference (*CM* − *SG*)
FA	1	15.785 ± 0.593	1 ($TV > 15.691$)	0.0
FB	1	7.455 ± 0.729	2-3 ($5.235 < TV < 10.667$)	+1.5
FC	2-3	6.924 ± 0.873	2-3 ($5.235 < TV < 10.667$)	0.0
FD	2-3	15.505 ± 1.514	1-2 ($13.367 < TV < 15.691$)	−1.0

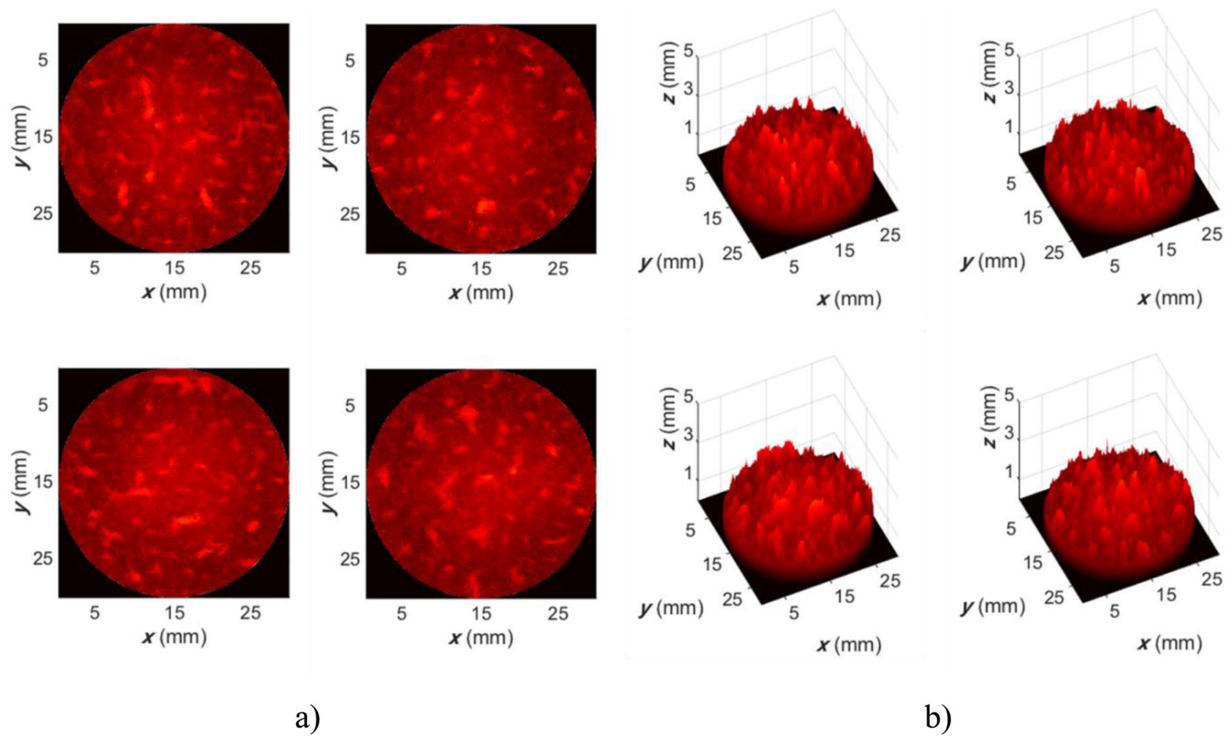

Figure 3. Reconstructed 3D images for the four abraded samples of the fabric *FA* seen (a) from a top view; and (b) from a perspective view.

shows the subjective grade (*SG*), the total volume of pilling (*TV*), the equivalent pilling grade based on the created correspondence model (*CM*) and the grade difference (*CM* - *SG*) for the fabrics *FA*, *FB*, *FC* and *FD*.

From Table 2, it is immediately identifiable that, concerning the two fabrics subjectively evaluated with grade 1, the fabric *FA* has more than the double of total volume of pilling comparatively to the fabric *FB*. For the other two fabrics subjectively evaluated with grade 2-3, the same is also verified, namely, the fabric *FD* has more than the double of total volume of pilling in comparison with *FC*. In addition, the grades of pilling attributed based on the correspondence model show to agree with this parameter. That is, a higher pilling formation was attributed to the fabrics with higher total volume of pilling (*FA* and *FD*) and a lower pilling formation was attributed to the fabrics with lower total volume of pilling (*FB* and *FC*). However, the pilling grades attributed subjectively make no distinctions between the fabrics *FA* and *FB*, and also between the fabrics *FC* and *FD*.

Figures 3–6 show the reconstructed 3D images obtained with the developed optical 3D-system for the four abraded samples of each of the fabrics *FA*, *FB*, *FC* and *FD*, respectively, in the two considering views (top view and perspective view).

Through observation of these figures, it can be seen that the fabrics that share the same subjective grades are in fact very different. In particular, the fabric *FA* has much more pilling formed in the surface of its abraded samples comparatively to the fabric *FB*, and exactly the same happens for the fabric *FD* comparatively to the fabric *FC*. Moreover, by looking to the reconstructed 3D images of the fabrics, *FA* shows to be more similar to *FD* rather than *FB*, and *FC* shows to be more similar to *FB* rather than *FD*.

The reconstructed images obtained for different pilling grades (1 to 5) shown in previous work (Mendes et al., 2010a) could also be considered for comparison with the reconstructed 3D images of the present study. Through this comparison, one can see that in fact *FA* and *FD* show an appearance more similar with a pilling grade 1, whereas *FB* and *FC* show an appearance more similar with a grade 2, or between a grade 2 and 3.

Based on these observations, and also on the calculations performed using the developed optical 3D-system, and on the comparisons performed between the pilling grades using the correspondence model and the subjective methodology, it can be confirmed that *FA* and *FC* correspond indeed to correct representations of fabrics with grade 1 and grade 2-3, respectively. On the other hand, the same criteria make us to conclude that the fabrics *FB* and *FD* seem to be pilling evaluation errors with an over-estimation of pilling formation in one and a half grades (+1.5) in the first case, and an under-estimation of pilling formation in one grade (-1.0) in the second case.

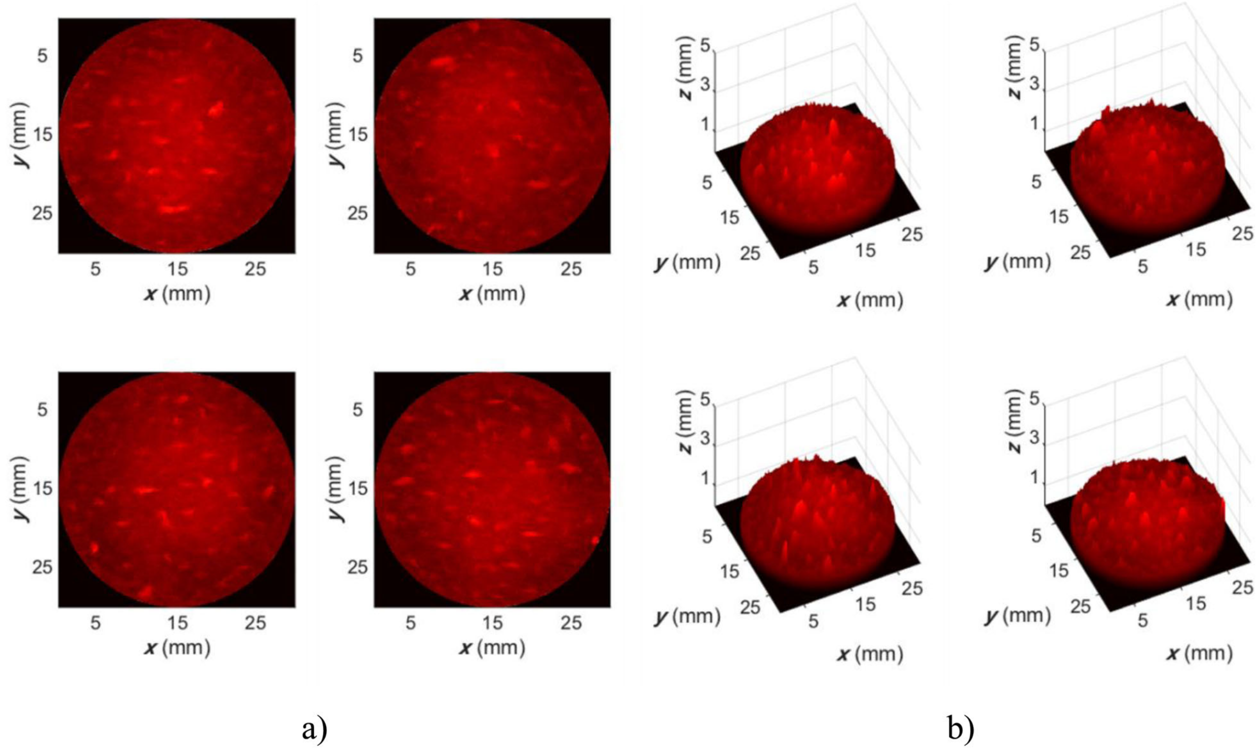

Figure 4. Reconstructed 3D images for the four abraded samples of the fabric *FB* seen (a) from a top view; and (b) from a perspective view.

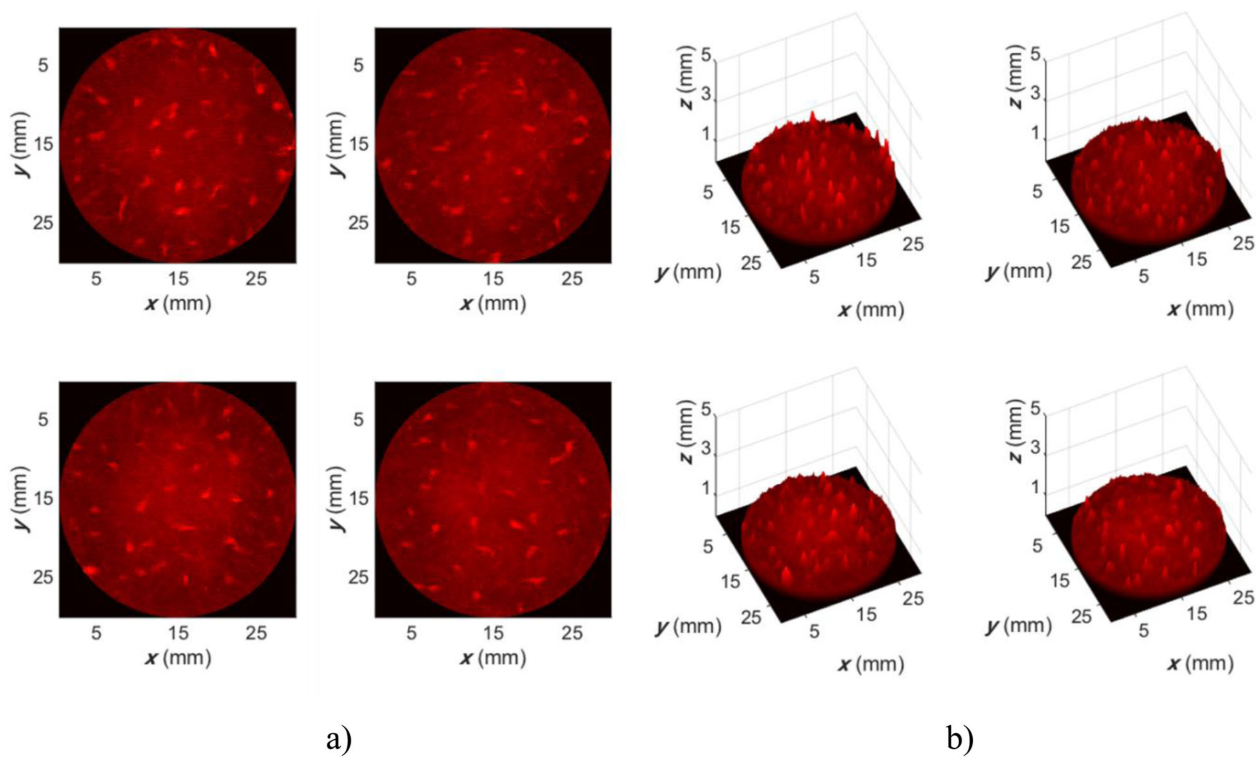

Figure 5. Reconstructed 3D images for the four abraded samples of the fabric *FC* seen (a) from a top view; and (b) from a perspective view.

But why the first two fabrics appear to have been correctly evaluated through visual inspection and the last two were not? From our experience, we know that there are some fabrics that are more difficult to analyze than other, such as fabrics with color patterns, fabrics that form a little number of very large pills only in a few locations of the surface, and fabrics that form a large number of very small pills on the entire surface. Fabrics *FB* and *FD* fall in the first two examples, and it seems that they may have confused the evaluators during their visual inspection. However, when these same fabrics were evaluated through use of the described optical 3D-system, they were properly assessed since the system detects the exact amount of pilling present in the surface of the fabrics, independently of the color pattern of the fabrics, since

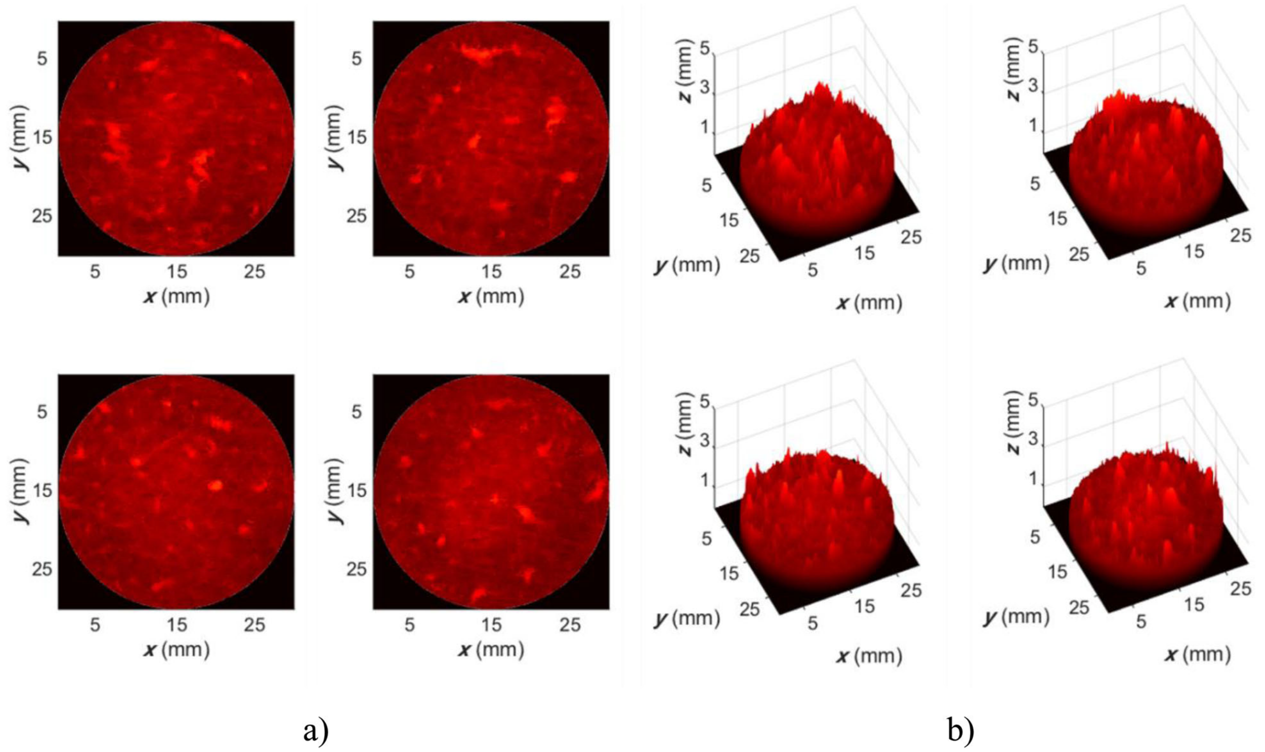

Figure 6. Reconstructed 3D images for the four abraded samples of the fabric *FD* seen (a) from a top view; and (b) from a perspective view.

the system is immune to this issue, and also independently of the pilling distribution in the fabrics.

Conclusions

In this work, an optical 3D-system was used to analyze four different fabrics with different grades of pilling. The fabrics *FA* and *FB* were subjectively evaluated with grade 1 and the fabrics *FC* and *FD* were subjectively evaluated with grade 2-3. Through use of the developed system, the corresponding 3D images of the fabrics were reconstructed, and the total volume of pilling was calculated for each fabric. It was verified that the fabric *FA* had a much more amount of pilling in the surface of the four abraded samples than the fabric *FB*. On the other hand, the fabric *FD* also revealed to have a much more amount of pilling formed than the fabric *FC*. The equivalent pilling grades attributed to the fabrics based on the correspondence model were different than the grades attributed by the evaluators (subjective method), having revealed to follow the total volume of pilling formed on the fabrics. Through observation of the corresponding 3D images reconstructed for each one of the four fabrics, it could be seen that in fact the fabrics are different and that the equivalent pilling grades based on the correspondence model seem to be more realistic representations of the pilling formation relatively to the grades given subjectively. In particular, the fabric *FB* appears to have been over-estimated, whereas the fabric *FD* appears to have been under-estimated when initially evaluated.

In conclusion, the subjective method for the pilling evaluation is a simple and easy method to be used, not requiring expensive equipment and it works very well in a vast number of cases. However, there are some fabrics that for some reason are more difficult to analyze than other, which may be more prone to evaluation errors. In these cases, it is convenient to have complementary methods that might assist the assessment of the fabrics to avoid evaluation errors that may happen. Our system has already been tested, and it shows to be a very useful complementary tool which may be helpful for quality control tests, supporting the standard method used by the textile industry for the evaluation of pilling.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Amirbayat, J., & Alagha, M. J. (1994). The objective assessment of fabric pilling.2. Experimental work. *Journal of the Textile Institute.*, *85*(3), 397–401. https://doi.org/10.1080/00405009408631284

Araújo, M., & Castro, E. M. M. (1987). *Manual de Engenharia Têxtil*. Fundação Calouste Gulbenkian.

Behera, B. K., & Mohan, T. E. M. (2005). Objective measurement of pilling by image processing technique. *International Journal of Clothing Science and Technology*, *17*(5), 279–291. https://doi.org/10.1108/09556220510616156

Binjie, X., & Hu, J. (2008). *Fabric appearance testing Fabric Testing ed J Hu.* (Chapter 6 pp 148–188)Woodhead Publishing Limited.

Chen, X., & Huang, X. B. (2004). Evaluating fabric pilling with light-projected image analysis. *Textile Research Journal.*, *74*(11), 977–981. https://doi.org/10.1177/004051750407401107

Cooke, W. D. (1985). Pilling attrition and fatigue. *Textile Research Journal.*, *55*(7), 409–414. https://doi.org/10.1177/004051758505500705

Eldessouki, M., Bukhari, H. A., Hassan, M., & Qashqari, K. (2014). Integrated computer vision and soft computing system for classifying the pilling resistance of knitted fabrics *Fibres Text. East. Eur*, *22*(6), 106–112.

Eldessouki, M., & Hassan, M. (2015). Adaptive neuro-fuzzy system for quantitative evaluation of woven fabrics' pilling resistance. *Expert Systems with Applications.*, *42*(4), 2098–2113. https://doi.org/10.1016/j.eswa.2014.10.013

Guan, S. Q., Shi, H. Y., & Qi, Y. Q. (2017). Objective evaluation of fabric pilling based on bottom-up visual attention model. *Journal of the Textile Institute.*, *108*(4), 597–604. https://doi.org/10.1080/00405000.2016.1176623

Hsi, C. H., Bresee, R. R., & Annis, P. A. (1998). Characterizing fabric filling by using image-analysis techniques – Part II: Comparison with visual pill ratings. *Journal of the Textile Institute.*, *89*(1), 96–105. https://doi.org/10.1080/00405009808658600

Jasinska, I., & Stempien, Z. (2014). An alternative instrumental method for fabric pilling evaluation based on computer image analysis. *Textile Research Journal.*, *84*(5), 488–499. https://doi.org/10.1177/0040517513512398

Kayseri, G. O., & Kirtay, E. (2015). Part II. Predicting the pilling tendency of the cotton interlock knitted fabrics by artificial neural network. *Journal of Engineered Fibers and Fabrics*, *10*(5), 62–71.

Kim, S. C., & Kang, T. J. (2005). Image analysis of standard pilling photographs using wavelet reconstruction. *Textile Research Journal.*, *75*(12), 801–811. https://doi.org/10.1177/0040517505059707

Konda, A., Xin, L. C., Takadera, M., Okoshi, Y., & Toriumi, K. (1990). Evaluation of pilling by computer image analysis. *Journal of the Textile Machinery Society of Japan*, *36*(3), 96–107. https://doi.org/10.4188/jte1955.36.96

Lucas, J., Miguel, R., Fiadeiro, P., Carvalho, M. L., Silva, M. S., & Mendes, A. (2010). Fabric Wrinkling evaluation by optical means Book. Proc. Int. Textile Clothing & Design Conf (pp. 642–646).

Mayekar, V. M., & Nachane, R. P. (2016). Fabric pilling – objective measurement system. *Indian Journal of Fibre and Textile Research.*, *41*(3), 338–343.

Mendes, A. O., Fiadeiro, P. T., & Miguel, R. A. L. (2006). *Three-dimensional surface reconstruction for evaluation of the abrasion effects on textile fabrics* [Paper presentation]. Proc. SPIE 6056 60560F.1-8 https://doi.org/10.1117/12.640438

Mendes, A. O., Fiadeiro, P. T., Miguel, R. A. L., & Lucas, J. M. (2009). Optical estimation of a set of pilling coefficients for textile fabrics. *Textile Research Journal.*, *79*(5), 410–417. https://doi.org/10.1177/0040517508095607

Mendes, A. O., Fiadeiro, P. T., Pereira, M. J. T., & Miguel, R. A. L. (2010a). Dual-scanning system for optical estimation of pilling formation. *Textile Research Journal.*, *80*(12), 1201–1213. https://doi.org/10.1177/0040517509355347

Mendes, A. O., Fiadeiro, P. T., & Miguel, R. A. L. (2010b). Subjective and objective pilling evaluations of textile fabrics: A comparison. *Textile Research Journal.*, *80*(18), 1887–1897. https://doi.org/10.1177/0040517510373636

Mendes, A. O., Fiadeiro, P. T., & Miguel, R. A. L. (2011). Virtual subjective pilling evaluation: An alternative. *Textile Research Journal.*, *81*(9), 892–901.

Mendes, A. O., Fiadeiro, P. T., Miguel, R. A. L., Lucas, J. M., & Silva, M. J. S. (2019). *Three-dimensional surface reconstruction for evaluation of wrinkling on textile fabrics* [Paper presentation]. Proc. SPIE, 11207 1120703.1-6

Montilla, M., Orjuela-Vargas, S. A., & Philips, W. (2014). *State of the art of 3D scanning systems and inspection of textile surfaces* [Paper presentation]. Proc. SPIE 9018 UNSP 90180A.1-7

Palmer, S., & Wang, X. G. (2003). Objective classification of fabric pilling based on the two-dimensional discrete wavelet transform. *Textile Research Journal*, *73*(8), 713–720. https://doi.org/10.1177/004051750307300809

Ramgulam, R. B., Amirbayat, J., & Porat, I. (1993). The objective assessment of fabric pilling.1. *Journal of the Textile Institute*, *84*(2), 221–226. https://doi.org/10.1080/00405009308631264

Technikova, L., Tunak, M., & Janacek, J. (2017). New objective system of pilling evaluation for various types of fabrics. *Journal of the Textile Institute.*, *108*(1), 123–131.

Telli, A. (2019). An image processing research consistent with standard photographs to determine pilling grade of woven fabrics. *Tekst. Konkeksiyon*, *29*(3), 268–276.

Xin, B. J., Hu, J. L., & Yan, H. J. (2002). Objective evaluation of fabric pilling using image analysis techniques. *Textile Research Journal.*, *72*(12), 1057–1064. https://doi.org/10.1177/004051750207201204

Xu, B. (1997). Instrumental evaluation of fabric pilling. *Journal of the Textile Institute.*, *88*(4), 488–500. https://doi.org/10.1080/00405000.1997.11090899

Yang, C. S., Lin, C. J., & Chen, W. J. (2019). Using deep principal components analysis-based neural networks for fabric pilling classification. *Electronics-Switz*, *8*(5), 474.1–474.10

Zhang, J. M., Wang, X. G., & Palmer, S. (2009). The robustness of objective fabric pilling evaluation method. *Fibers and Polymers*, *10*(1), 108–115. https://doi.org/10.1007/s12221-009-0108-7