

A computational method for the investigation of burn scars topology based on 3D optical scan

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ARTICLE INFO

Keywords:

3D scanning
Burn scars
Roughness
Gaussian filtering
Wavelet filtering

ABSTRACT

Burn scar treatment is a difficult subject to address since the improper therapy can have a significant impact on people's quality of life. The evaluation of medical therapy over time should be based on objective measurement of the severity of burn scars and their progression. Unfortunately, most clinical assessments of scars are still reliant on physicians' subjective exams of patients. A profitable method to overcome the limitations of subjective assessment could be to leverage 3D scanning technologies. These could be used to retrieve the surface topology of burns. Accordingly, the goal of this study is to provide an objective approach for analysing the surface topology of burn scars using 3D scanning and roughness-based evaluation. In particular, two types of ISO-compliant profile and surface filters (Gaussian and Wavelet) derived from the analysis of roughness in the mechanical sector are implemented to discriminate form from roughness of scars. Once retrieved, the roughness surface is processed to derive a set of statistical parameters describing the scar surface topology. Three case studies were used to derive these parameters (a synthetic surface, an ostrich-skin surface and a set of scars). After the surface's roughness was determined, a comparison between healthy and unhealthy skin could be established. The devised methods prove their effectiveness in correctly retrieving the main surface characteristics of a burn scar. Therefore, by using the proposed method it will be possible to evaluate the effectiveness of medical therapy by comparing the healthy and scarred skin of a single subject.

1. Introduction

Burn scars can lead to cosmetic and functional issues that limit daily living activities, prevent people from resuming their usual social roles, and lower quality of life. According to data, there are between 2 and 29 hospitalized burn injuries for every 100.000 people in Europe [1]. Fire or flame are the most frequent causes of burns, followed by hot items, electricity and chemicals. After burn injuries, hypertrophic scarring is estimated to occur between 8% and 67% [1]. Moreover, in 25–68% of patients, sensory complaints, including pain and itching persist even after clinical healing [2]. Burn scar treatment is a challenging issue to deal with since a wrong therapy can have a substantial influence on people's quality of life. The evaluation of medical treatment over time should be based on objective measurement of the severity of burn scars and of their evolution. Unfortunately, the current clinical assessment of scars is mostly based on clinicians' subjective examinations of patients [3,4]. To this purpose, a number of subjective rating scales are used to evaluate parameters related to the scar severity. The foremost

commonly used scales are the Vancouver Scar Scale (VSS) and the Patient and Observer Scar Assessment Scale (POSAS) [3,5]. Such scales are mainly used to compare scar characteristics of a single patient over time rather than among different individuals [6]. Moreover, these evaluations are observer-dependent and, therefore, are characterised by limited inter-scar correspondence. As a consequence, scars with different characteristics may be classified in the same severity class (i.e. the same score is provided by the clinician) thus leading to the same kind of medical treatment [7]. In order to improve the assessment of scar burns severity by using VSS or POSAS, the patient's opinion is often acquired; unfortunately, patient's perception and subjective evaluation was proved to be easily distorted by emotional involvement [8]. To further improve the reliability of subjective assessment scales, Van der Wal et al. proposed the following clinimetric requirements to be satisfied [9]:

- Reliability: refers to the reproducibility and internal consistency of ratings (also considering the measurement error).

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<https://doi.org/10.1016/j.combiomed.2022.105945>

Received 4 May 2022; Received in revised form 8 July 2022; Accepted 6 August 2022

Available online 15 August 2022

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Nomenclature			
α	Constant according to ISO 16610-20	f_s	Spatial sampling frequency
$\lambda_s, \lambda_c, \lambda_f$	Cut-off length – Nesting Index length	L_c	Truncation constant
$\Gamma_{1D}(x)$	Gaussian 1D weighting function in the x-direction	$K(x)$	Kernel of the profile filter
$\Gamma_{1D}(y)$	Gaussian 1D weighting function in the y-direction	$K(x,y)$	Kernel of the areal filter
$\Gamma_{1Df}(\lambda)$	Fourier transform of Γ_{1D}	Sa	Arithmetical mean height of the surface
$\Gamma_{2D}(x,y)$	Gaussian 2D weighting function	Ssk	Kurtosis of the surface
Δ	Percentage deviation	Sp	Maximum peak height of the surface
Δx	Spatial resolution	Sq	Root mean square of the surface
Δf	Spatial frequency resolution	Ssk	Skewness of the surface
$\psi(x)$	Mother Wavelet	Sp	Maximum pit height of the surface
$\psi_{ab}(x)$	Wavelet function	Sv	Maximum height of the surface
$\psi_{m,n}(x)$	Discrete Wavelet function	$w(x)$	Filtered profile
$\Psi_{WT}(a,b)$	Wavelet transform	$w(x,y)$	Filtered surface
a	Scaling parameter	$z(x)$	Unfiltered profile
b	Shifting parameter	$z(x,y)$	Unfiltered surface
cA	Approximation Wavelet coefficient	DWT	Discrete Wavelet Transform
cD	Detail Wavelet coefficient	HH	2D DWT Diagonal detail coefficient
f_c	Spatial centre frequency	HL	2D DWT Rows detail coefficient
f_{cA}	Spatial frequency content in cA	LH	2D DWT Columns detail coefficient
f_{cD}	Spatial frequency content in cD	LL	2D DWT Approximation coefficient
		$POSAS$	Patient and Observer Scar Assessment Scale
		VSS	Vancouver Scar Scale

- Validity: indicating whether the rating scale is measuring what needs to be measured.
- Responsiveness: i.e. the ability of the scale to detect clinically significant changes.
- Feasibility: regarding the user-friendliness of the rating scale.

However, even by implementing the above-mentioned requirements, none of the scales proposed so far covers the full range of clinical features and are only able to detect macroscopic differences [9]. Moreover, most of them need at least two observers to obtain reliable results thus limiting the clinical applicability.

2. Background

To overcome the limitations of subjective rating scales, several devices for objectively measuring a range of scar features are available in clinical practice, mostly based on reflectance spectroscopy, laser imaging and stereo photogrammetry. As reported by Lee et al. [10], these devices are used to retrieve several parameters such as colour, size, surface topography or roughness of the scar, biomechanical properties, pathophysiological disturbances and tissue microstructure. As reported by Draaijers et al. [8] the aforementioned parameters, especially the visually characterizable ones, have a significant influence in the general opinion. Particularly, scar thickness and roughness are significant visual characteristics of the scar and have a significant impact on the patient's perception. Such a parameter can be evaluated by using both indirect

and direct methods. Indirect methods are based on the manufacture of a negative-positive skin cast replica and subsequent analysis with mechanical profilometry devices [11,12]. This methodology, although accurate, can be time consuming and hard to be used directly in the clinical environment. Direct methods, instead, use available 3D-based devices on the market, such as the Phase shift Rapid In Vivo Measurement Of the Skin (PRIMOS Omniscan, GF Messtechnik GmbH; Germany) [4,13] and the Visioscan VC 98 (Courage + Khazaka, Germany) [14]. The PRIMOS system, a structured light 3D scanner, was applied to scar severity assessment by Bloemen et al. [13,15]. Calculation of surface roughness was carried out within an area of 38.90 by 28.86 mm. Three parameters are used to characterize the scar: the number of peaks (Pc), the arithmetic mean of the roughness of the area (Sa), and the mean of the five deepest valleys and the highest peaks (Sz) [13]. The Visioscan VC 98 is a high-resolution UVA light camera that uses the Surface Evaluation for Living Skin (SELS) method to evaluate skin roughness. Four parameters are calculated to quantitatively describe the skin surface while a qualitative evaluation is performed by analysing the scar images' grey levels. The evaluated parameters are: skin smoothness ($Sesm$), skin roughness (Ser), scaliness ($Sesc$) and wrinkles (Sew) [14]. Unfortunately, this system, although promising in the analysis of skin roughness, has a measurement area of 6×8 mm, which is too small to analyse wide burn scars. Other systems based on stereophotogrammetry were used to analyse skin roughness. Lumenta et al. [16] demonstrated that the Lifeviz Micro camera system (Quantificare S.A., Sophia Antipolis, France) allows to detect surface irregularities much better than

Table 1

Comparison of surface topography measuring devices in terms of parameter measured, correlation with clinical score.

Device	Parameter	Correlation with clinical score	Portability	Issues	Reference
PRIMOS	Surface roughness (PC , Sa , Sz)	Correlation with POSAS: $r = 0.617$	Yes	Small area section, Single scan from a single position	Bloeman et al. [13]
Visioscan VC98	Skin parameters ($Sesm$, Ser , $Sesc$, Sew)	Not been used in scars	Yes	Small area section, Single scan from a single position	Kottner et al. [14]
Lifeviz Micro	Surface Irregularity	Performed better than subjective visual assessment	Yes	Not defined area section, Single scan from a single position	Lumenta et al. [16]
	Surface roughness (Sq , Sa , Ssk , Sku , Sv , Sz , Sp)	Not been used in scars	Yes	Small area section, Single scan from a single position	Petit et al. [17].
Self-Developed 3D Camera	Surface roughness (Sa , Sq)	Not been used in scars	Yes	Not defined area section, Single scan from a single position	Kim et al. [18]

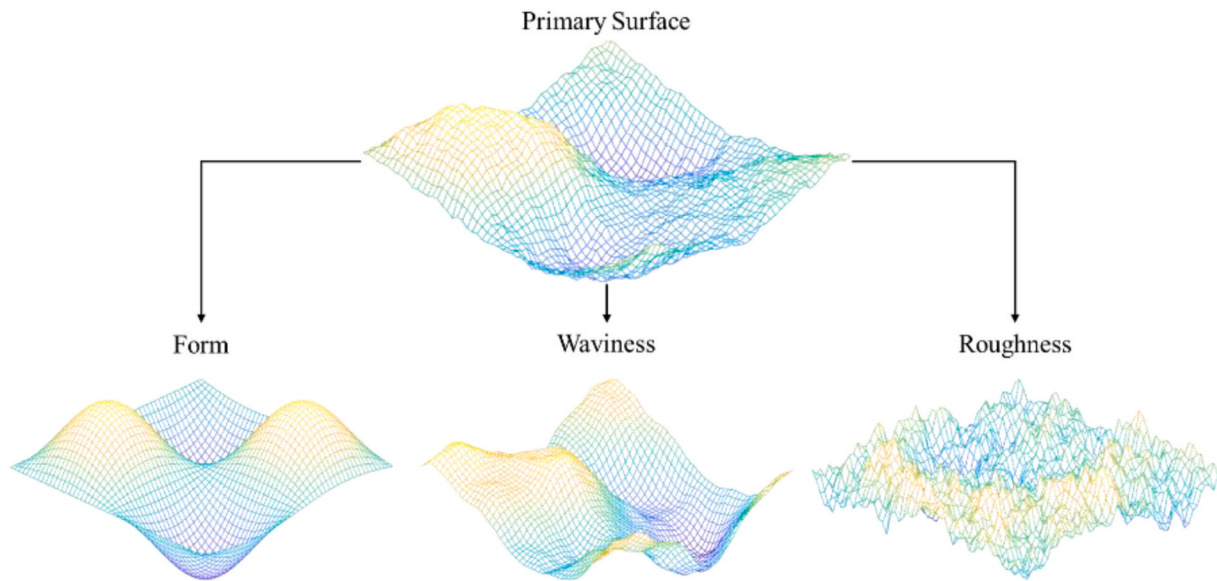


Fig. 1. Surface components of an exemplificative primary surface after high-frequency noise removal.

subjective visual assessment. Petit et al. [17] used the LifeViz Micro to perform an objective repeatable quantification of severity of atrophic acne scarring by characterising their properties using a number of statistical parameters derived from surface state analysis. A target area of 30×30 mm was defined on the face. Kim et al. used a self-developed 3D camera system (Stereomage Optical Topometer, Korea University, Seoul, Korea) to calculate the arithmetic mean of the roughness of the area (S_a) and mean square roughness (S_q) for acne scars before and after six weeks of treatment with Autologous Dermal Fibroblast Culture [18]. Table 1 summarizes the previously listed devices used for measuring surface topography.

3. Proposed methodology

To the best of authors' knowledge, no scientific works dealing with the objective characterisation of burn scar surfaces that make use of professional 3D scanners are currently available. Such devices, while not specifically designed for biomedical use, have the great advantage to allow the retrieving of large areas with high resolution and from multiple positions, thus overcoming the system limitations outlined above. Therefore, their use for the investigation of burn scars is worth to be considered and this technology could be a game-changer for the objective study of skin burns. In fact, the reliable retrieval of the 3D geometry of the burned area could allow to investigate the topological changes with respect to the healthy skin areas i.e. to measure a number of characteristics, which differentiate healthy from unhealthy skin.

In this scenario, the present work investigates the surface topology of burn scars by leveraging 3D scanning and roughness-based assessment. In fact, by applying on 3D scans of burned skin a number of methods and tools derived from the investigation of roughness in the mechanical field (with particular reference to the ISO standards), the scar topology is retrieved and analysed. Moreover, a set of statistical parameters, typically used to describe mechanical surfaces, are computed and used to provide a preliminary description of the actual surface status. The reminder of the paper is as follows. First, a general description on surface metrology methods is provided in sections 4.1 and 4.2, mainly focused on 1D and 2D filtering of 2D and 3D signals, respectively (i.e. to deal with both a profile and a surface analysis of the area of interest). Then in section 4.3, a number of significant statistical parameters describing the surface morphology is identified. Three case studies are included in section 5 and are taken into account for: 1) define the lower limits for 2D Gauss filtering and for 2D Wavelet analysis, 2) define the

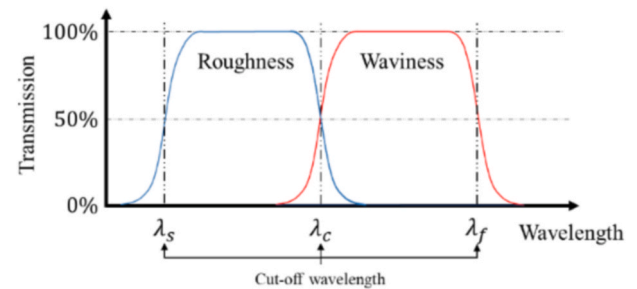


Fig. 2. Conceptual drawing of profile method.

best filtering parameters for discriminating form and roughness of the analysed surface and 3) provide a set of roughness parameters characterizing the burned surface. In particular in section 5.1, the method is initially applied on synthetic 3D data to set a starting value for setting the filters implemented. Then in 5.2, the method is tested on the 3D acquisition of an ostrich leather sample to determine the filtering parameters, which allows discriminating shape from roughness in a sample resembling human skin, but with a regular pattern on it. Eventually in section 5.3, thanks to the participation of three voluntaries, three different burn scars are acquired by using a commercial scanner, i.e. the Artec Space Spider 3D [19].

4. Surface topology characterization

In surface metrology, adequate characterisation of the topography and subsequent calculation of representative surface parameters is essential to correlate with the parameters of the manufacturing process and the quality. Parameters for the calculation of two-dimensional roughness according to ISO 4287 [20] and ISO 4288 [21] were introduced long ago but are still suitable for standard process monitoring. As widely recognized, any surface can be subdivided into three components called shape, waviness and roughness. Furthermore, a noise contribution resulting from the instrumental error is present on the 3D datum. By suppressing the noise, the primary surface can be retrieved (see Fig. 1).

Unfortunately, there is no precise threshold to separate the components; therefore, defining which portions of the surface texture contribute to roughness or not is a subjective decision and depends on the application field. This means that, the type of filter and the values

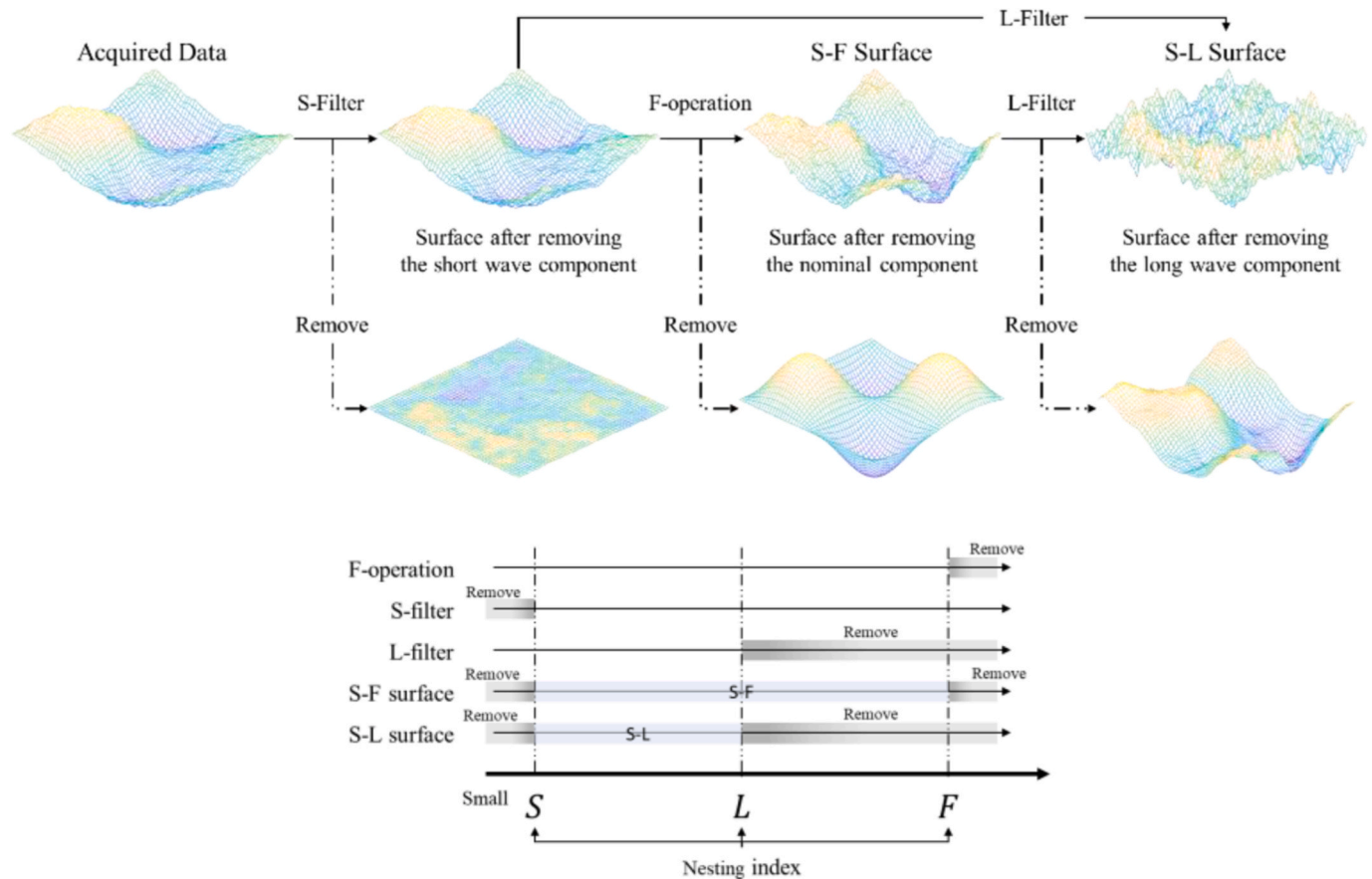


Fig. 3. Conceptual drawing of the areal method.

used as cut-off wavelengths determine the frequency bandwidth that defines the roughness. A cut-off wavelength is a threshold for profile filter indicating 50% transmission factor for a given amplitude. For this purpose according to ISO 4287 [20], regarding the 2D profile analysis, three types of filters are defined (see Fig. 2):

- λ_s filter: designating the threshold between the roughness component and shorter wave components,
- λ_c filter: designating the threshold between the roughness component and waviness components,
- λ_f filter: designating the threshold between the waviness component and longer wave components.

The roughness profile is separated from the waviness component by means of the λ_c profile filter utilizing the cut-off wavelength λ_c , after initial noise (λ_s profile filter) and form filtration (λ_f profile filter) are carried out. The above-mentioned profile filters are expanded to areal filters in the ISO 25178-2 standard [22]. In detail, the so-called F-operator is used for form removal, S-filter is used for small wavelength and L-filter is for major scale. The cut-off wavelength adopted for these operators is called “nesting index”, according to the nomenclature introduced by the aforementioned standard [22]. With reference to Fig. 3, the S-filters, that are typically areal Gaussian filters, are used to remove the short wave component. As a second step, the nominal form component of the primary surface is removed by means of the F-operator, thus obtaining the S-F surface. If the nominal shape cannot be clearly defined, as in the case of topographic analysis of scars’ surface, form filters such as second-order Gaussian regression filters according to ISO 16610-1 [23], can be applied [24] to this aim. Finally, using the L-filter, the S-L surface, i.e. the roughness, can be derived from the primary surface. Differently from the two-dimensional case, in which

the roughness and waviness profiles are obtained after filtering the primary profile, in areal filtering two surfaces are defined by ISO 25178-2 [22].

Referring to the choice of cut-off values for the profile method, these are defined by the series $\lambda_c = \dots; 0.08 \text{ mm}; 0.25 \text{ mm}; 0.8 \text{ mm}; 2.5 \text{ mm}; \dots$ according the standard ISO 3274 [25]. In addition, as specified in ISO 4288 [21], the cut-off value must be chosen based on the estimated surface roughness; a value $\lambda_c = 8 \text{ mm}$ is, for instance, recommended for roughness varying in the range $10 < Ra \leq 80 \mu\text{m}$. The evaluation of the profile parameters must be done in a specific finite size range of the entire profile. Moreover, ISO 4287 [20] specifies that the evaluation profile length needs to be at least five times the sampling length, respectively cut-off wavelength. Unlike the profile method, only recommendations for the nesting index are given in ISO 25178:2 [22], listing a series of numbers as follows:

[..., 0.1mm; 0.2mm; 0.25mm; 0.5mm; 0.8mm; 1.0mm; ...]

The evaluation area is not strictly constrained as in the two-dimensional case; in fact in ISO 25178-2 [22] only the shape of the evaluation area is defined to be square or rectangular.

4.1. 1D Filter

As mentioned above, the choice of filtering method is often arbitrary thus influencing the results. Accordingly, it is crucial to select an appropriate filter to discriminate components with different wavelengths, with the aim of observing and characterising only the components of interest. The ISO series of standards dealing with profile and areal filters are part of ISO 16610 [23] and extensively describes linear filtering strategies such as Gaussian, Spline and, more recently, also filters that have the capability of partitioning a profile into multiple fine

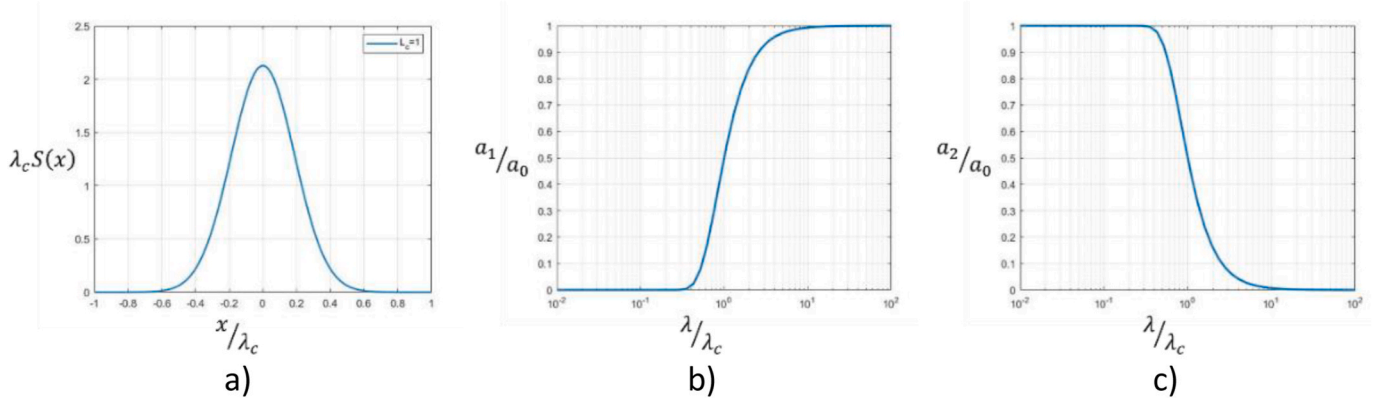


Fig. 4. Weighting function of the Gaussian Filter (a), long (b) and short (c) transmission characteristics of the Gaussian Filter.

bandwidths (known as multi-scale filters) [26]. Among the latter, Wavelet-based filtering and its application in surface metrology is an active research topic [27,28]. The filtering operation to extract a specific wavelength components of the profile $z(x)$ can be described with the mathematical formulation, according to ISO 16610-20 [29], as follows:

$$z(x) \xrightarrow{\text{filter}} w(x) \quad (1)$$

where $w(x)$ is the filtered profile. The linear filtering operation determines a moving average, the values are weighted differently in the averaging process. This function is also known as “weighting function” or kernel $K(x)$ of the filter, which determines the proprieties of the filter. Determination of a moving average can be expressed as an integral for profile filtering:

$$w(x) = \int K(x - \xi) z(\xi) d\xi \quad (2)$$

Where ξ is the variable of integration in the x direction. This operation is also referred to as convolution where the values of the weighting function $K(x)$ are reflected over the ordinate before the integration occurs. In the present work, the Gaussian and the Wavelet filters are analysed.

4.1.1. 1D Gaussian Filtering

The weighting function of the Gaussian filter, according to ISO 16610-21 [30], is given by:

$$\Gamma_{1D}(x) = \frac{1}{\alpha \lambda_c} e^{\left[-\pi \left(\frac{x}{\alpha \lambda_c} \right)^2 \right]} \quad (3)$$

where:

- x is the distance from the centre (maximum) of the weighting function.
- λ_c is the cut-off wavelength.
- α is a constant; to provide 50% transmission characteristic at the cut-off λ_c , α is given by: $\sqrt{\frac{\ln 2}{\pi}}$.

For the proposed implementation, the weighting function is an interval equal to $-L_c \lambda_c < x < L_c \lambda_c$ where L_c is a truncation constant. The transmission characteristics can be obtained by performing the Fourier transform of the continuous function $\Gamma_{1D}(x)$. The transmission characteristics of the long-wave components, Fig. 4, is given by Ref. [26]:

$$\Gamma_{1Df}(\lambda) = \int_{-\infty}^{\infty} \Gamma_{1D}(x) e^{i\lambda x} dx = \int_{-\infty}^{\infty} \frac{1}{\alpha \lambda_c} e^{\left[-\pi \left(\frac{x}{\alpha \lambda_c} \right)^2 \right]} e^{i\lambda x} dx = e^{\left[-\pi \left(\frac{\alpha \lambda_c}{\lambda} \right)^2 \right]} = \frac{a_1}{a_0} \quad (4)$$

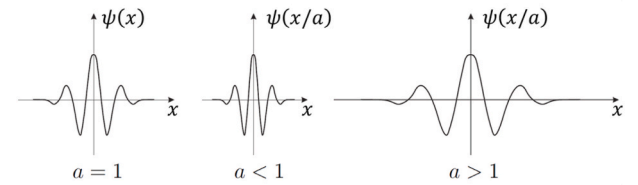


Fig. 5. Example of wavelet dilation as the scale parameter a changes.

where:

- a_0 is the amplitude of a sinusoidal wave profile before filtering.
- a_1 is the amplitude of the long-wave component of a sinusoidal wave profile.
- λ is the wavelength of this sinusoidal profile

The transmission characteristic of the short-wave component (see Fig. 4) is complementary to the transmission characteristic of the long-wave filter, which can be expressed as:

$$\frac{a_2}{a_0} = 1 - \frac{a_1}{a_0} = 1 - e^{\left[-\pi \left(\frac{\alpha \lambda_c}{\lambda} \right)^2 \right]} \quad (5)$$

Where:

- a_2 is the amplitude of the short-wave component of a sinusoidal wave profile.

It should be noted that the typical Gaussian filter has steep transmission properties, making it impossible to get tight partitioning of the profile into multiple-wavelength bandwidths.

4.1.2. 1D Wavelet filtering

Unlike the Gaussian filter, some wavelets provide steep transmission characteristics and enable partition of profiles into narrow bandwidths. In fact, a wavelet-based filter produces a series of filtered profiles, each of which corresponds to a certain wavelength bandwidth. As known, the wavelet function is defined as:

$$\psi_{ab}(x) = \frac{1}{\sqrt{a}} \psi\left(\frac{x-b}{a}\right) \quad (6)$$

where:

- ψ is the mother wavelet
- a is the scaling parameter
- b is the shifting parameter

Table 2

DWT passbands at seven levels of decomposition with a spatial sampling frequency of 10 mm⁻¹ and associated cut-off.

Level	DWT Detail Bandwidth [mm ⁻¹]	Cut-off Wavelength λ_c [mm]		
1	2.50	5.00	0.40	0.20
2	1.25	2.50	0.80	0.40
3	0.63	1.25	1.60	0.80
4	0.31	0.63	3.20	1.60
5	0.16	0.31	6.40	3.20
6	0.08	0.16	12.80	6.40
7	0.04	0.08	25.60	12.80
...	...	...	...	...

The mother wavelet is contracted and dilated by changing the scaling parameter a , as shown in Fig. 5. The change in scale a modifies not only the spatial centre frequency f_c of the wavelet, but also the length of the window. The translation parameter b specifies the position of the wavelet in space.

The wavelet function used to transform the signal (or profile) $z(x)$ is defined as follows:

$$\Psi_{WT}(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} z(x) \psi^* \left(\frac{x-b}{a} \right) dx \quad (7)$$

Where ψ^* is the complex conjugate of the mother wavelet. Decreasing the scale a , i.e. using a shorter window, will increase the spatial resolution Δx resulting in a decrease in the spatial frequency resolution Δf . This implies that the spatial frequency resolution Δf is proportional to the frequency f , i.e. the wavelet analysis has a constant relative spatial frequency resolution. For the present implementation, the Discrete Wavelet Transform (DWT) is used, where the discretization of the parameter b must be linked to that of the parameter a , as follows:

$$\begin{cases} a = a_0^{-m} & a_0 > 1 \ m \in \mathbb{Z} \\ b = nb_0 a_0^{-m} & b_0 > 1 \ n \in \mathbb{Z} \end{cases} \quad (8)$$

Discretizing on a dyadic grid, i.e. for $a_0 = 2$ and $b_0 = 1$, the equation of the DWT is obtained as follow:

$$\psi_{m,n}(x) = 2^{\frac{m}{2}} \psi(2^m x - n) \quad (9)$$

A wavelet family is made up of two filters: a scaling function that works as a low-pass filter and a wavelet filter that operates as a bandpass filter. For each level of analysis, the profile is decomposed into two components called approximation and detail: the first contains the longer wavelengths and the second contains the shorter wavelengths. The profile containing the approximations can be decomposed into two additional components. For a p -level decomposition, the highest observed spatial frequency in the approximation wavelet coefficients can be calculated as a function of the spatial sampling frequency f_s as:

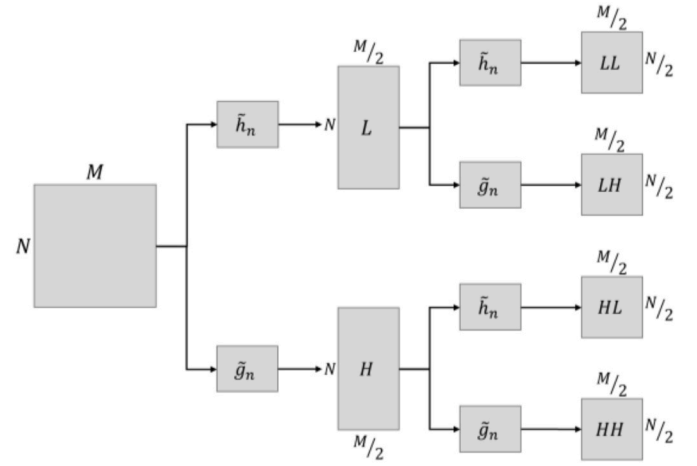
$$f_l = \frac{f_s}{f^{p+1}} \quad (10)$$

The theoretical spatial frequency content in the approximation cA and detail cD profiles can be calculated as:

$$f_{cA} = [0, 2^{-p-1} f_s]; f_{cD} = [2^{-p-1} f_s, 2^{-p} f_s] \quad (11)$$

Table 2 shows the decomposition bandwidths of the detail profiles for a profile sampled with a spatial frequency of 10 mm⁻¹ (i.e. a sampling step of 0.1 mm) and the relative wavelength of the cut-off obtained from the level by inverting the values of the spatial frequencies at each decomposition level.

Unlike the Gaussian filter, where the cut-off wavelength λ_c choice is arbitrary, in a multiscale filtering it is only a function of the initial spatial sampling rate.

**Fig. 6.** Implementation of 2D wavelets.

4.2. 2D Filter

Both filtering methods are generalizable to the two-dimensional case i.e. to applications on surfaces. Similarly to 1D case, if $K(x, y)$ is the weighting function or kernel of the areal filter, the general linear areal filter for a surface $z(x, y)$ can be expressed by a double integral:

$$w(x, y) = \iint K(x - \mu; y - v) z(\mu, v) d\mu dv \quad (12)$$

Where $w(x, y)$ is the filtered surface, μ and v are the variables of the integration in x and y directions respectively. As in the previous case, the filtering operation is a convolution and, if the weighting function is separable, equation (12) can be expressed as two single integrals:

$$w(x, y) = \int K(x - \mu) \left[\int K(y - v) z(\mu, v) dv \right] d\mu \quad (13)$$

This means that both the kernels and the convolution are separable. As a consequence, the convolution can be computed in two steps, utilizing profile filters instead of areal filters, by filtering first in one direction and then in the other.

4.2.1. 2D Gaussian Filtering

ISO 16610-61 [31] specifies the metrological characteristics of the Gaussian areal filter. The weighting function for a surface has as equation a symmetric Gaussian function in both directions x and y with cut-off wavelength equal to λ_c (nesting index):

$$\Gamma_{2D}(x, y) = \frac{1}{\alpha^2 \lambda_c^2} e^{-\frac{\pi}{\alpha^2} \left(\frac{x^2 + y^2}{\lambda_c^2} \right)} \quad (14)$$

Also the linear planar Gaussian weighting function is separable. It can be expressed as a product of two linear open profile Gaussian weighting function, as shown in the following equation:

$$\Gamma_{2D}(x, y) = \Gamma_{1D}(x) \Gamma_{1D}(y) = \frac{1}{\alpha \lambda_c} e^{-\left[\frac{\pi}{\alpha^2} \left(\frac{x}{\lambda_c} \right)^2 \right]} \frac{1}{\alpha \lambda_c} e^{-\left[\frac{\pi}{\alpha^2} \left(\frac{y}{\lambda_c} \right)^2 \right]} \quad (15)$$

The transmission characteristics can be obtained by performing the Fourier transform of the continuous function $\Gamma_{2D}(x, y)$, and as shown in the ISO 16610:61 [31], they are the same as for the profile filtering (Fig. 4).

4.2.2. 2D Wavelet filtering

As in the case of Gaussian Filter, also 2D DWT can be divided into separable and non-separable design methods, with the first-class dividing transform operations into row and column processes that can

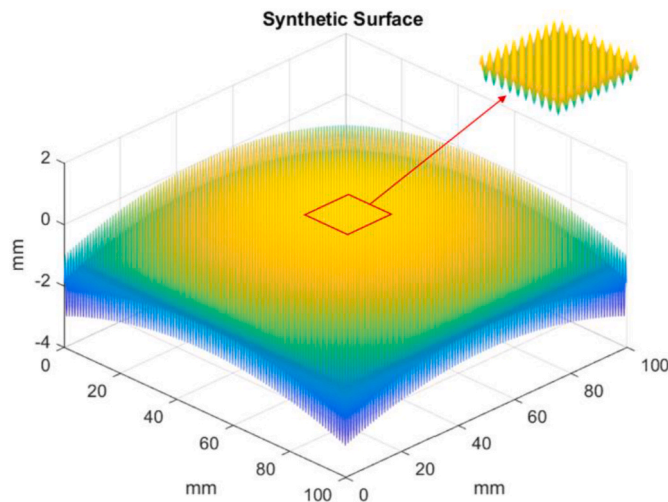


Fig. 7. Synthetic primary surface with paraboloid shape and sinusoidal components.

be individually done by the 1D-DWT architecture [32,33]. As shown in Fig. 6, operating first along the rows, the coefficients obtained from low-pass filtering (L) are determined in the upper branch and the coefficients obtained from high-pass filtering (H) are determined in the lower branch. The same procedure is then applied to all columns. This results in a matrix of four bands (LL , HL , LH , HH). The LL band contains a coarse version of the image (longer wavelength). The other three bands contain the details (shorter wavelength) showing respectively: HL band highlights the discontinuities along the rows, the LH band those along the columns, and the HH band will contain the discontinuities along the oblique direction. As for the one-dimensional decomposition, the LL matrix can be decomposed into other sub-matrices up to the desired level.

4.3. Surface parameters

The parameters for surface characterisation are defined by ISO 25178-2 [23]. Height, hybrid, miscellaneous, function and associated, and spatial are the five parameters defined by the aforementioned standard. As demonstrated in Ref. [34], the height parameters are the most frequently used compared to the others, although the spatial parameters can provide more information about the surface structure. In the present study the following parameters are used for scar burn characterization:

- average height parameters: Sa is the arithmetical mean of the absolute surface heights, Sq is a root mean square (rms) value of surface amplitudes.
- extreme parameters: Sp is the maximum peak height, Sv is the maximum valley depth, Sz is the sum of the previous two.
- distribution parameters Skewness Ssk is the ratio of the average cube value of the surface ordinates to the cube of the Sq parameter, Kurtosis Sku is the ratio of the average quartic value of the surface ordinates to the fourth power of the Sq parameter.

5. Test, validation and results

One of the main aims of this work is to adopt the aforementioned filtering methods for investigating the surface of burn scars and for extracting a number of parameters related to the surface roughness and waviness. In fact, these parameters could provide useful statistical information on the scar anatomy. Consequently, the method is firstly tested on a synthetic surface to assess the general applicability of the ISO-based filtering strategies and to find their limits of applicability.

Table 3

Roughness values calculated from Gaussian filtering.

Parameter	Target [mm]	Nesting Index for the Gaussian filter					
		$\lambda_c = 0.8mm$		$\lambda_c = 2.5mm$		$\lambda_c = 8mm$	
		[mm]	Δ [%]	[mm]	Δ [%]	[mm]	Δ [%]
Sa	0.42	0.25	-40.32	0.42	0.00	0.42	0.00
Sq	0.50	0.29	-41.00	0.50	0.00	0.50	0.00
Sz	2.00	1.18	-41.00	2.00	0.00	2.00	0.00
Sp	1.00	0.59	-41.00	1.00	0.00	1.00	0.00
Sv	1.00	0.59	-41.00	1.00	0.00	1.00	0.00
Ssk	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Sku	2.25	2.25	0.00	2.25	0.00	2.25	0.00

Based on the results observed using synthetic surface, a second case study is carried out to retrieve the 3D scanning of an ostrich leather fabric. This sample resembles human skin but with a series of quasi-regular patterns and can be considered a good baseline for determining the optimal setting for the two different filters adopted in this work. Therefore, the scope of ostrich leather investigation is twofold: 1) it allows to find the optimal values for Gaussian nesting index and to determine the best decomposition level when using Wavelet filtering; 2) it allows verifying the compliance of extracted statistical parameters with the expected surface topology. The aforementioned values for nesting index and wavelet decomposition are finally adopted to deal with an actual 3D scanning of burns, so that the statistical parameters suggested by the ISO standards can be evaluated on real cases.

5.1. Synthetic surface study

As mentioned above, to verify the general applicability of the ISO-based filtering strategies, a synthetic primary surface of size 100×100 mm was artificially generated within the Matlab® environment. The surface (see Fig. 7) is a paraboloid with the addition of sinusoidal components. These components simulate a roughness with a known amplitude of 1 mm and a period of 1 mm. This range is selected to set a lower limit for actual scars topology, as the authors are planning to characterize burn scars with minimum size in the order of millimetres. Since no noisy data are present, the synthetic surface can be treated as an S-F surface where the instrumental noise has already been removed.

For surface S-F, the validation of the implemented filters aims at finding the nesting index of L-filter to discriminate the waviness surface from the roughness. Since the surface morphology is known a-priori, the roughness values obtained after filtering can be compared directly with their actual values. In other words, the values for Sp and Sv should correspond to the amplitude (0.5 mm) and Sz should be twice as large (1 mm). In addition, Ssk should be close to zero as the added synthetic structures are symmetrical. As described in the method, both Gaussian and Wavelet filtering are considered in this work. In case of Gaussian filtering, some recommended values of the ISO 25178 [22] standard (i.e. 0.8, 2.5 and 8 mm) were selected as nesting indexes. Table 3 summarizes the aforementioned parameters values for the considered surface and the percentage deviation Δ from the target values.

As far as the wavelet decomposition is concerned, the synthetic surface was decomposed on six levels and the details referred to the second to the sixth levels were summed up, simulating respectively a nesting index of 0.8, 1.6, 3.2, 6.4 and 12.8 mm (see Table 2). Furthermore, the family of “Biorthogonal” wavelets is chosen referring to ISO 16610-29 [35], specifically the “BIOR 4.4”. Table 4 shows the calculated roughness parameters and the percentage deviation Δ from the target values.

Surface roughness evaluation after Gaussian filtering shows consistent results for a nesting index λ_c greater than 2.5 mm, the calculated parameters correspond to the target values. It should be specified that by using a cut-off wavelength close to the period of the added component, the filters are not able to separate the surfaces correctly, due to the

Table 4
Roughness values calculated from wavelet filtering.

Parameter	Target [mm]	Level details for the DWT decomposition									
		2Level – 0.8mm		3Level – 1.6mm		4Level – 3.2mm		5Level – 6.4mm		6Level – 12.8mm	
		[mm]	Δ [%]	[mm]	Δ [%]	[mm]	Δ [%]	[mm]	Δ [%]	[mm]	Δ [%]
Sa	0.42	0,21	–50.00	0.42	0.00	0.42	0.00	0.42	0.00	0.42	0.00
Sq	0.50	0,26	–48.00	0.50	0.00	0.50	0.00	0.50	0.00	0.50	0.00
Sz	2.00	1,41	–29.50	2.00	0.00	2.00	0.00	2.00	0.00	2.00	0.00
Sp	1.00	0,78	–22.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
Sv	1.00	0,63	–37.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
Ssk	1.00	0,00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sku	2.25	2,84	26.22	2.25	0.00	2.25	0.00	2.25	0.00	2.25	0.00

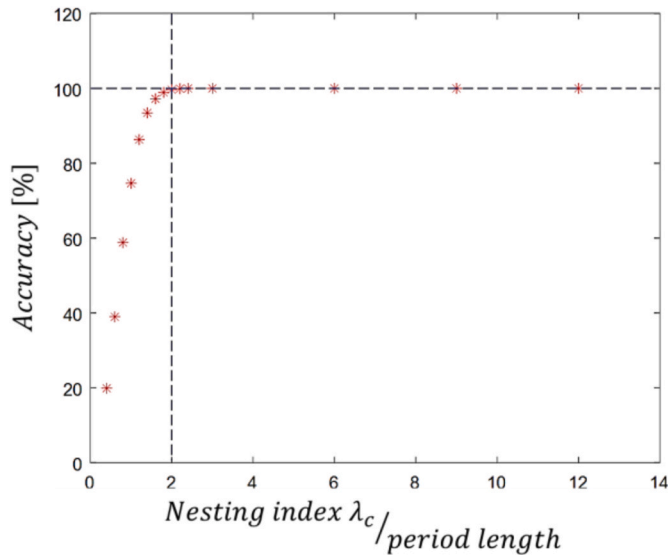


Fig. 8. Roughness value calculation accuracy versus nesting index λ_c /period length.

Table 5
Technical specifications artec space spider.

Technical Specifications Artec Space Spider	
3D point accuracy. up to	0.05 mm
3D resolution. up to	0.1 mm
Working distance	200–300 mm
Linear field of view. H × W closest range	90 × 70 mm
Linear field of view. H × W furthest range	180 × 140 mm
Angular field of view. H × W	30 × 21°
Ability to capture texture	Si
Texture resolution	1.3 MP
Colors	24 bpp
3D reconstruction rate for real-time fusion. up to	7.5 fps
Data acquisition speed. up to	1 mln points/s
2D/3D exposure time	0.0002 s
3D light source	Blue LED
2D light source	White 6 LED array
Interface	1 × USB 2.0. USB 3.0 compatible

transmission characteristic, which allows 50% transmission for the given amplitude (see Fig. 4). For Gaussian filtering it is possible to evaluate the accuracy of the results with respect to the ratio of the nesting index to the period of the added component. As demonstrated by Pomberger et al. in Ref. [36] the nesting index should be at least twice the period of the added component to obtain a satisfying roughness calculation accuracy, as shown in Fig. 8.

This evaluation is not applicable to the wavelet filtering since in this case the resulting nesting index only depends on the spatial sampling frequency. Surface roughness evaluation after Wavelet filtering shows

consistent results for a decomposition level higher than 3. From the analysis of the synthetic surface, it emerges that at least a nesting index equal to 2.5 mm (for Gaussian filtering) and a decomposition level equal to 3 (for Wavelet) are required to reliably discriminate roughness parameters in the stated lower limit for burn scars.

5.2. Ostrich leather

The method was also tested on a sample of “ostrich leather”. The surface has a roughly equally-spaced pattern of small bulges called follicles. This typology of surface is selected to simulate the presence of burn areas with strong differences in terms of topology with the healthy areas. The sample was acquired with a commercial 3D scanner i.e. the Artec Space Spider 3D scanner [19] whose technical specifications are shown in Table 5. The surface, approximately 200 × 150 mm in size, was acquired in three different configurations, laying it on a plane, a cylinder, and a free-form surface, respectively.

The point clouds obtained from the scans were imported into a commercial Reverse Engineering software (i.e. Geomagic Design X) where they were processed in order to: 1) clean of any accidental error due to the scanning process; 2) resample them as a 2.5D mesh, i.e. without undercuts relative to the vertical direction, chosen as reference. The resampling was performed with a resolution equal to that of the acquisition instrument, i.e. 0.1 mm. The resampled three-dimensional surface can be described as a matrix, with a constant sampling step in the two directions, whose elements correspond to the height of the surface under examination. Fig. 9 visually shows the results of this post-processing phase.

The implemented filters were applied obtaining the three characteristic surfaces S , $S - F$ and F described by ISO 25178 [22]. As demonstrated in the previous case study, the nesting index should be greater than 2.5 mm to deal with burn scars. Accordingly, different nesting indices were applied to the acquired surfaces for the F-operator, i.e. 15, 20 and 25 mm. These nesting indices were chosen by evaluating the size of the ostrich skin follicles, approximately 10 mm. Referring to Fig. 8, it was shown that proper separation of components is achieved for a nesting index greater (two times) than the period of the components to be separated. The nesting index chosen for the S-filter, following ISO 25178 [22], was 0.5 mm. This is the minimum recommended value for a sampled surface at 0.1 mm. For the wavelet decomposition, the surfaces were decomposed to seven levels and the details of the first two levels were used for the reconstruction of the S-surface. The details of the fifth to seventh levels were then added together to simulate various wavelengths of cut to compose the S-F surface. Finally, the approximation of the last layer will represent the surface F. As depicted in Fig. 10, the increase of both the nesting index for the Gaussian filter and of the decomposition level for the wavelet filter lead to an S-F surface where the follicles are neglected. Consequently, also the roughness values increase as shown in Tables 6 and 7.

In fact, roughness parameters such as Sz , Sv and Sp show significantly higher values when the nesting index or decomposition level increases. The Ssk value, unlike the synthetic surface, is close to zero when

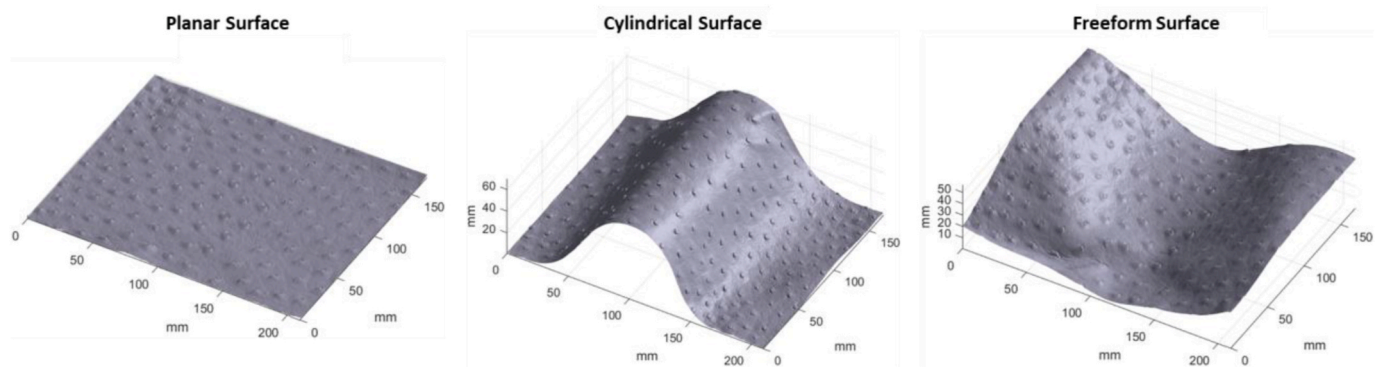


Fig. 9. Acquired surfaces in planar, cylindrical and free-form shape.

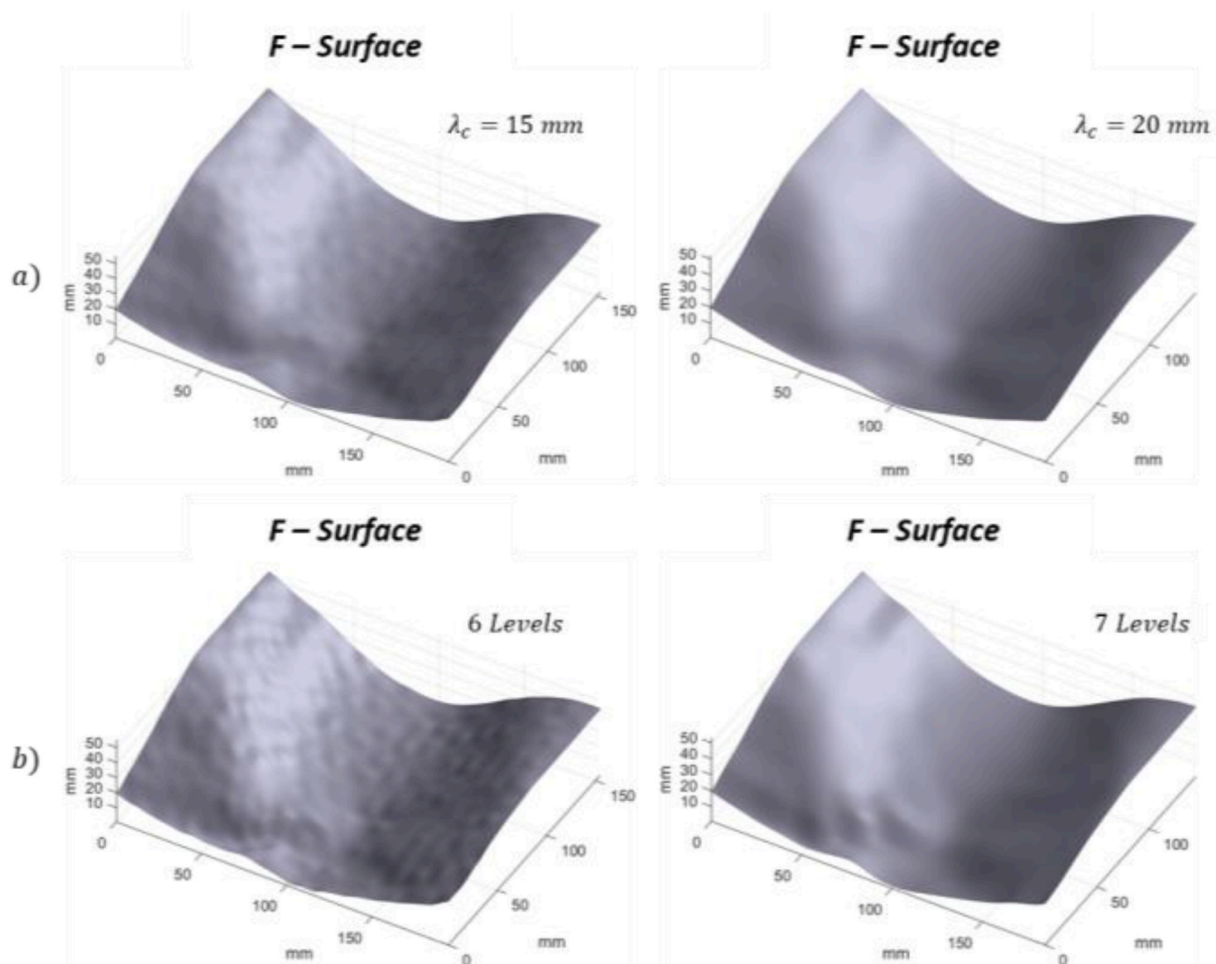


Fig. 10. F-Surface for the free-form shape ostrich leather at the change of nesting index and decomposition level.

considering Gaussian filtering for the cylindrical and Free-Form surfaces indicating a balance between peaks and valleys, while for the other filtering it is different from zero. This agrees with what was expected, as the surface under examination has peaks such as follicles and not as many valleys. The decrease in Sku values implies a surface roughness comprising more wavelengths, resulting in a smoother shaped surface.

Observing the roughness values of the seven-level decomposition (corresponding to a cut-off length of 25.60 mm) and the filtering with $\lambda_c = 25$ mm they do not differ significantly from each other, especially for the planar surface, which in fact does not present a pronounced shape and therefore wavelengths in addition to the surface structures. It

was to be expected that the results, referring to the same surface, would be more in line with each other. These variations can be ascribed to the form of the starting surface, but more importantly to the resampling technique used to generate a 2.5D mesh. This process is always susceptible to error, the size of which will depend on both the number of undercuts in the surface and the direction of resampling. From the results obtained above, it is possible to state that for the analysis of scanned data of surfaces resembling human skin with a set of topological errors, a nesting index varying in the range [15–20 mm] and a decomposition level greater or equal to 6 are the most interesting to be investigated for real scars. For these reasons, these values are taken into

Table 6
Roughness values calculated from Gaussian filtering.

Parameter	Nesting Index for the Gaussian filter								
	<i>Planar</i>			<i>Cylindrical</i>			<i>Free – Form</i>		
	<i>S – Filter$\lambda_c = 0.5mm$</i>			<i>S – Filter$\lambda_c = 0.5mm$</i>			<i>S – Filter$\lambda_c = 0.5mm$</i>		
	15mm	20mm	25mm	15mm	20mm	25mm	15mm	20mm	25mm
<i>Sa</i>	0.09	0.11	0.12	0.19	0.30	0.42	0.13	0.17	0.22
<i>Sq</i>	0.14	0.16	0.18	0.27	0.38	0.52	0.19	0.25	0.30
<i>Sz</i>	1.63	1.76	1.86	3.59	4.47	5.37	2.34	2.82	3.32
<i>Sp</i>	0.95	1.06	1.13	2.21	2.75	3.25	1.44	1.68	1.85
<i>Sv</i>	0.68	0.69	0.73	1.39	1.72	2.11	0.91	1.14	1.48
<i>Ssk</i>	2.18	2.18	2.10	1.11	0.66	0.40	1.27	0.84	0.49
<i>Sku</i>	10.34	9.32	8.70	7.35	5.16	3.99	7.46	6.22	5.64

Table 7
Roughness values calculated from wavelet filtering.

Parameter	Level details for the DWT decomposition								
	<i>Planar</i>			<i>Cylindrical</i>			<i>Free – Form</i>		
	<i>NumberofDetailLevel</i>			<i>NumberofDetailLevel</i>			<i>NumberofDetailLevel</i>		
	5	6	7	5	6	7	5	6	7
<i>Sa</i>	0.04	0.09	0.13	0.08	0.15	0.23	0.05	0.11	0.19
<i>Sq</i>	0.07	0.14	0.20	0.12	0.22	0.34	0.09	0.16	0.28
<i>Sz</i>	1.58	1.81	2.09	3.10	3.63	4.33	1.90	2.21	4.09
<i>Sp</i>	0.79	0.95	1.28	1.64	2.26	2.92	0.99	1.31	2.53
<i>Sv</i>	0.79	0.85	0.81	1.46	1.37	1.41	0.91	0.91	1.88
<i>Ssk</i>	0.10	1.21	1.98	0.56	1.65	1.29	0.13	1.20	1.20
<i>Sku</i>	19.33	8.41	8.26	17.78	10.77	8.42	17.11	8.30	8.99

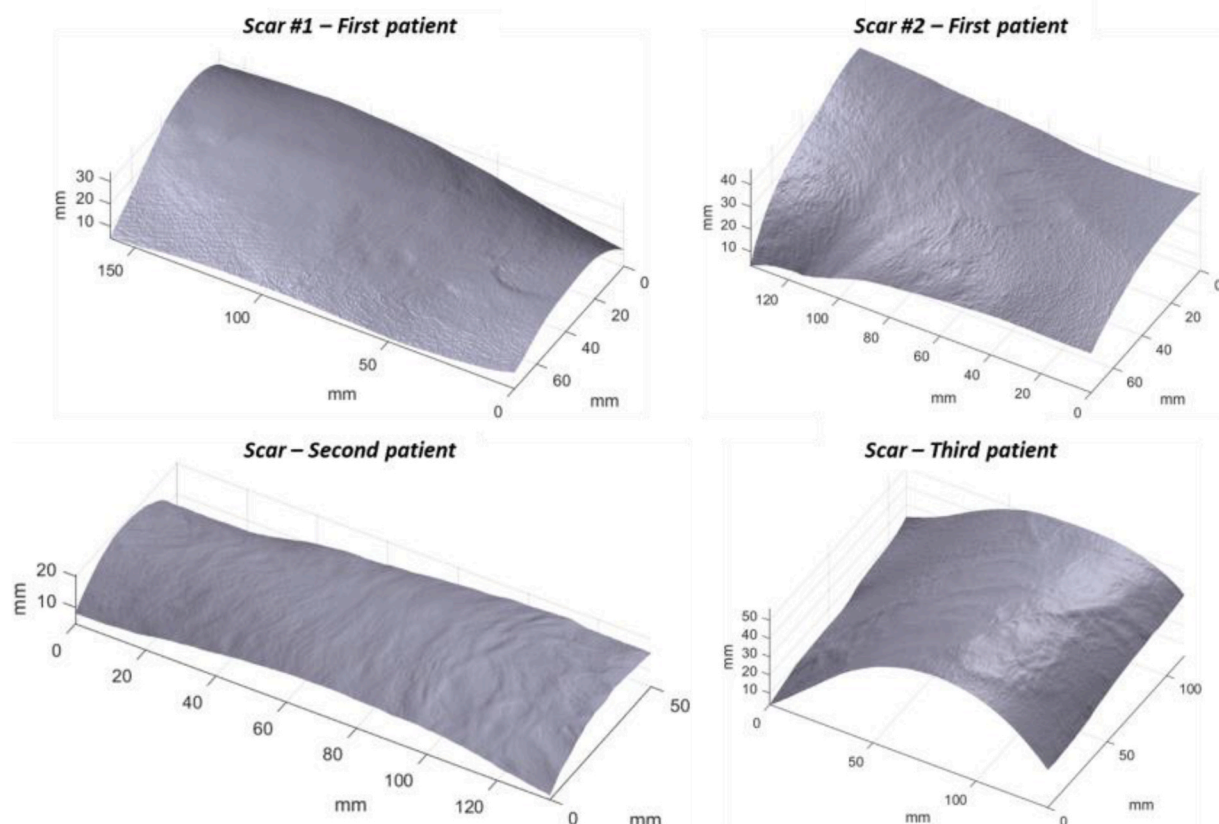


Fig. 11. Acquired scars.

Table 8

Scars roughness values calculated from Gaussian filtering.

Parameter	Gaussian filter – Scar							
	Scar #1 – First Patient		Scar #2 – First Patient		Second Patient		Third Patient	
	$S - \text{Filter}\lambda_c = 0.5\text{mm}$		$S - \text{Filter}\lambda_c = 0.5\text{mm}$		$S - \text{Filter}\lambda_c = 0.5\text{mm}$		$S - \text{Filter}\lambda_c = 0.5\text{mm}$	
	15mm	20mm	15mm	20mm	15mm	20mm	15mm	20mm
<i>Sa</i>	0.05	0.08	0.05	0.06	0.07	0.08	0.07	0.09
<i>Sq</i>	0.07	0.10	0.06	0.08	0.09	0.11	0.09	0.12
<i>Sz</i>	0.84	0.92	0.68	0.87	1.00	1.16	0.88	1.00
<i>Sp</i>	0.40	0.39	0.44	0.58	0.46	0.55	0.38	0.49
<i>Sv</i>	0.45	0.53	0.35	0.29	0.54	0.61	0.50	0.52
<i>Ssk</i>	−0.64	−0.59	0.94	0.95	−0.33	−0.24	0.15	0.26
<i>Sku</i>	5.04	4.58	6.02	5.19	4.64	4.31	4.23	3.73

Table 9

Healthy Tissues values calculated from Gaussian filtering.

Parameter	Gaussian filter – Healthy Tissue					
	First Patient		Second Patient		Third Patient	
	$S - \text{Filter}\lambda_c = 0.5\text{mm}$		$S - \text{Filter}\lambda_c = 0.5\text{mm}$		$S - \text{Filter}\lambda_c = 0.5\text{mm}$	
	15mm	20mm	15mm	20mm	15mm	20mm
<i>Sa</i>	0.03	0.05	0.03	0.03	0.03	0.03
<i>Sq</i>	0.04	0.06	0.04	0.04	0.04	0.04
<i>Sz</i>	0.51	0.43	0.30	0.34	0.47	0.46
<i>Sp</i>	0.29	0.19	0.18	0.21	0.29	0.25
<i>Sv</i>	0.22	0.24	0.12	0.14	0.24	0.21
<i>Ssk</i>	−0.51	−0.32	0.65	0.63	0.30	0.22
<i>Sku</i>	3.72	2.90	4.25	4.16	5.79	4.43

account also for the next case study.

5.3. Test on burn scars

Four burn scars from three different subjects were analysed using the same procedure described in the previous section. Informed consent was obtained from the patient or legal tutor, and patients' data for analysis were anonymised. In addition, the corresponding antimere, i.e. the healthy symmetrical body's part, was acquired whenever possible so that roughness parameters could be obtained on portions of non-scar tissue as well. Fig. 11 shows the images of the acquired scars.

As mentioned above, for the Gaussian filter the two values 15 and 20 mm are chosen for the cut-off λ_c . For the wavelet filter, the surface was instead decomposed into seven levels and the details up to the sixth and seventh level were added together. The healthy surfaces were filtered using the same settings in order to compare healthy with burned skin. Tables 8 and 9 show the obtained results for Gaussian filtering, Tables 10 and 11 show the Wavelet filtering one.

Again, roughness parameters such as *Sz*, *Sv* and *Sp* show significantly higher values as the nesting index or decomposition level increases. Like the previous case, the decrease in *Sku* values implies a S-L surface that

includes more wavelengths. Comparing the results between scars and portions of healthy skin, in all cases there is a clear decrease in values. The values of *Sa* and *Sq* for the healthy skin portions show similar and comparable values for both Gaussian and DWT filtering, while show a significant variation for each scar. Fig. 12 shows the scanned surface's deviation of the second scar from the shape obtained after Gaussian filtering with a nesting index of 15 mm. It is possible to observe the greater uniformity of the healthy skin in comparison with the scar. The uncoloured part is the area eliminated after filtering to avoid the invalidation of the results obtained.

For the case studies reported, a nesting index equal to 15 mm and 6 levels of decomposition for the Wavelet can be considered adequate. This is further demonstrated in Tables 9 and 11. As expected the calculated roughness values for healthy tissue differ significantly from those for scar one. The average height parameters, such as *Sa* and *Sq*, in all cases undergo a clear decrease as well as the extreme parameters. Regarding distribution parameters, also in this case as for the ostrich skin, the value of *Ssk* is not close to zero indicating a different concentration of peaks and valleys. This confirms what was expected, as the scars have significant surface irregularities. Using a 3D scanner like the Artec Space Spider, the presented methodology, can be applied to

Table 11

Healthy tissues roughness values calculated from wavelet filtering.

Parameter	Wavelet Decomposition – Healthy Tissue					
	First Patient		Second Patient		Third Patient	
	<i>NumberofDetailLevel</i>		<i>NumberofDetailLevel</i>		<i>NumberofDetailLevel</i>	
	6	7	6	7	6	7
<i>Sa</i>	0.03	0.14	0.03	0.09	0.03	0.06
<i>Sq</i>	0.04	0.17	0.04	0.12	0.04	0.08
<i>Sz</i>	0.72	0.98	0.41	0.71	0.44	0.76
<i>Sp</i>	0.46	0.61	0.23	0.36	0.22	0.37
<i>Sv</i>	0.26	0.38	0.18	0.35	0.22	0.39
<i>Ssk</i>	−0.42	0.48	−0.26	0.07	0.24	−0.25
<i>Sku</i>	5.37	2.29	4.45	2.67	4.77	4.57

Table 10

Scars roughness values calculated from wavelet filtering.

Parameter	Wavelet Decomposition – Scar							
	Scar #1 – First Patient		Scar #2 – First Patient		Second Patient		Third Patient	
	<i>NumberofDetailLevel</i>		<i>NumberofDetailLevel</i>		<i>NumberofDetailLevel</i>		<i>NumberofDetailLevel</i>	
	6	7	6	7	6	7	6	7
<i>Sa</i>	0.05	0.11	0.04	0.09	0.07	0.11	0.06	0.15
<i>Sq</i>	0.06	0.14	0.05	0.11	0.09	0.15	0.08	0.22
<i>Sz</i>	0.83	1.17	0.82	0.92	1.10	1.16	1.05	1.81
<i>Sp</i>	0.42	0.65	0.51	0.50	0.48	0.58	0.53	1.10
<i>Sv</i>	0.41	0.52	0.31	0.42	0.62	0.58	0.53	0.71
<i>Ssk</i>	−0.14	0.27	−0.07	0.41	−0.26	0.01	−0.03	1.54
<i>Sku</i>	6.16	3.10	7.00	3.40	5.92	3.65	6.43	6.91

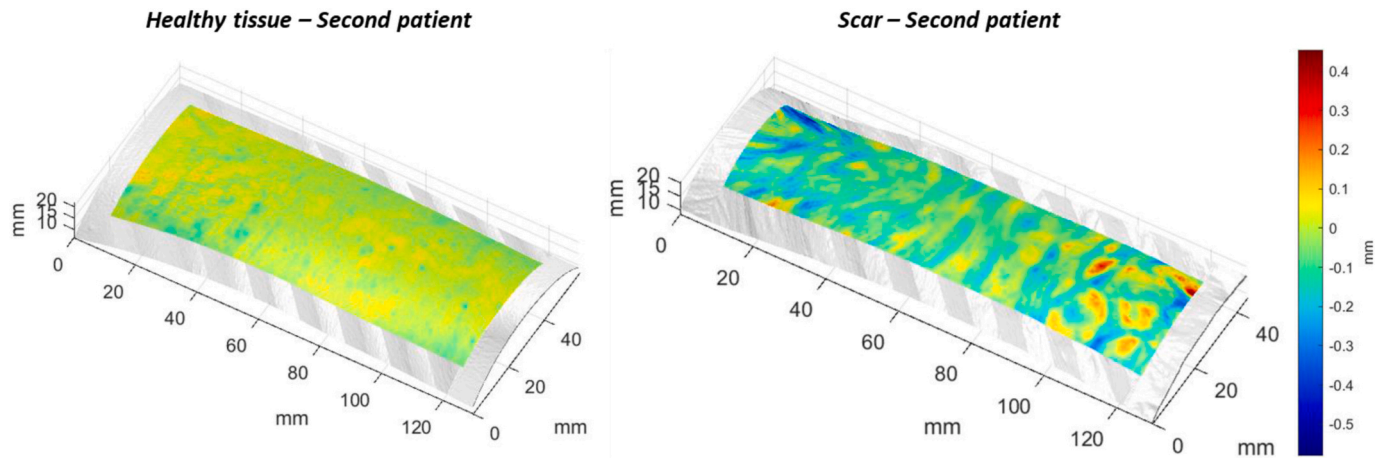


Fig. 12. Healthy and scar tissue comparison after Gaussian filtering with $\lambda_c = 15$ mm

extract objective parameters describing the surface of burn scars. These parameters can be used to monitor an individual patient's progress over time; the monitoring should be based on the change in these parameters, e.g. if Sa decreases or Ssk approaches zero. This characterization can be considered correct for a single-patient monitoring. If this methodology were to be used for the creation of a severity index in collaboration with hospital staff, an extensive clinical trial and subsequent data collection will be required. By analysing a large set of scars, it will be possible to scale (dimensionless) the parameters and make the characterization independent of the individual patient. Currently, it is not possible to determine whether a given roughness value can be considered "normal" regardless of the patient's scar characteristics.

6. Conclusions

Utilizing 3D scanning and roughness-based analysis, the present study investigates the surface topology of burn scars. The main objective of this work was to draft a preliminary method for objectively investigating the surface topography of burn scars with the final aims of 1) separating the effect of roughness and form from a 3D acquisition of the scars, and 2) deriving a set of statistical parameters to be used for characterizing the surface. Currently, there are no scientific publications dealing with the professional 3D scanners' objective characterisation of burn scar surfaces. The main advantage of these devices is that they allow high-resolution acquisition of large areas from different locations, thus avoiding the limitations of the systems described in Section 2. In order to provide a preliminary description of the current state of the surface, a number of statistical parameters that are frequently used today to describe mechanical surfaces are calculated and used. Some of these parameters, shown in Table 2, have been used in previous works. However, several of the described parameters have never been utilized to characterize burn scars. Two types of ISO-compliant profile and surface filters (Gaussian and Wavelet) were described and implemented. This allowed obtaining comparable numerical values based on a reproducible, time invariant and non-invasive procedure. By analysing the results obtained for a set of case studies, it is possible to assert the capability of both implemented methods in consistently separating the contributions of roughness and form, under a series of reasonable assumptions. In fact, from the analysis of the synthetic surface, it was possible to define both the optimal value of the Gaussian nesting index (i.e. 2.5 mm) and the decomposition level for Wavelet (i.e. equal to 3). Such values allowed a reliable discrimination of roughness parameters in a range that can be considered a "lower limit" for burn scars. By applying the method on ostrich leather, it was possible to state that a nesting index varying in the range [15–20 mm] and a decomposition level greater or equal to 6 are the most interesting to be investigated for

real scars. From a preliminary analysis of actual scars, it was possible to demonstrate that nesting index values of 15 mm and 6 levels of decomposition are good starting values for their characterization. However, patients' scars may differ significantly from those examined in this exploratory study in terms of size, form, and roughness. Therefore, the suggested values for Gaussian and Wavelet filtering could not be adequate for discriminating form and roughness of all scars. In fact, by observing the roughness values obtained after filtering, it is possible to notice the complexity in the choice of the nesting index or decomposition level. However, a suitable nesting index for Gaussian filtering can be somehow derived by directly evaluating the size of the scar under investigation. In particular, as demonstrated for the synthetic surface, it is possible to consider that a nesting index equal to the double of the average size of an examined scar can discriminate form from roughness. This freedom in the choice of nesting index cannot be achieved in DWT analysis, thus implying the need of performing an extensive analysis of scar surfaces to determine the best choice for the decomposition level. DWT analysis is not unique as it is dependent on the chosen mother wavelet and the sampling step of the surface. To obtain different cut-off levels (Table 2), it is necessary to resample the surface with a different sampling step. Furthermore, if the proposed method is used to monitor the time course of a patient's scar, it will be necessary to use the same nesting index or decomposition level for the successive characterizations. Once the roughness profile is correctly extracted, a number of statistical parameters was computed and a comparison between healthy and unhealthy skin was performed. The proposed study has some limitations. In fact, as previously stated, it allows to extract a number of statistical parameters which describe the geometry of the scar. However, how these parameters are related to the actual condition of the patients is still a matter of investigation. This is particularly true when dealing with conditions such as pain, pruritus and scar contracture. On the other hand, the proposed method will be useful to understand how the topology of a scar changes over time, especially during treatments. Therefore, future works will be addressed on the collection of a relevant number of scar parameters to build a consistent dataset. Once such data are available it will be possible to use the statistical parameters for inferring the severity of the burn scars in a more objectively manner, possibly also leveraging IA-based algorithms for the classification and the severity assessment.

Declaration of competing interest

'None Declared'.

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