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Application of a Computational Method Based on 3D Scans for Burn Scar Topology Characterisation

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Abstract. The treatment of burn scars is a much discussed and sensitive topic because an improper therapy can have a significant impact on the quality of people's lives. To accurately assess both the health of scars and the outcomes of treatment, the medical evaluation should be based on objective measurements of progression over time. To overcome the limitations of subjective assessment is to leverage, 3D scanning technologies can be used to acquire topological information about the lesions and extract a set of relevant statistical parameters describing them. Accordingly, the present work aims at addressing both efficiency and reliability of a preliminary method based on the objective investigation of the surface topography of burn scars by applying it on several patients of the Meyer Children's Hospital burns department. A commercial 3D scanner is used to acquire 3D data relative to the scars of five patients. By applying a method based on the computational analysis of scan data, a significant number of roughness-related parameters are retrieved. This information is used to create a coherent dataset that allows the severity of burn scars to be inferred objectively. The developed method facilitates the evaluation of treatment efficacy by assessing wound healing during follow-up visits.

Keywords: 3D scan, Burn scar, Surface roughness
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1 INTRODUCTION

Burn injuries are among the most common forms of skin injuries reported by hospital and emergency rooms. In most cases, they are caused by fire, heat, or hot substances. Burn injury fatality rates have reduced dramatically in recent years, due to the advent of more improved first aid procedures and the adoption of more innovative first aid tools, though to a limited extent in poor nations. The treatment of burns does not end with first aid, as it is necessary to treat the scarred skin for many years, and in some cases for life. For this reason, scar treatment can be divided into two consecutive phases: first aid, which occurs immediately after the event, and long-term therapies, which aim to eliminate potential problems not only of an aesthetic nature, but also disabilities caused by the resulting contractures. In general, injuries take on the shape of the surrounding tissue due to a secondary process in which the wound site shrinks over time due to the condensation of surrounding cells. Scars are classified as depressed, atrophic, or raised based on their morphology, (classification by contour). Despite the fact that this classification is intended to make doctors' work easier, we can find scars that are totally different in terms of topology, severity, extension and so on within the same category. For these reasons, and in order to choose the best scar therapy, it is critical to define and employ a scar evaluation method as objective as possible to assess the course and success of the treatment process itself.

Current wound evaluation and follow-up treatment methods do not provide an objective and unique assessment of the skin's scarred health status, because they are based on subjective assessment scales such as the Vancouver Scar Scale (VSS) and the Patient and Observer Scar Assessment Scale (POSAS) [16]. These scales are used to compare scar characteristics of a single patient over time rather than between different patients. They also totally depend on the observer. Unfortunately, there are currently no gold standards for assessing scar severity. The primary reason for this is that most current scar assessment methods focus on the aesthetic characteristics or concerns associated with scars [3].

In the study written by "*Furferi et al.*" a method based on 3D evaluation techniques is proposed to objectively estimate the roughness values of the scar [7]. In this article, a preliminary method is proposed for the objective investigation of the surface topography of burn skin based on the transposition of ISO 4287 [8] and ISO 4288[9], which are referred to methods for surface evaluation in the mechanical field. In detail, in such a preliminary work, the best setting for filtering the 3D data acquired on scars by means of a commercial 3D scanner is defined. In particular, the best options for applying 2D Gaussian filter and wavelet-based decomposition are proposed by adhering to the principles of the ISO series standard for production process parameters and quality evaluation.

The main goal of the current work is twofold, based on the results obtained on synthetic specimens discussed in the previous study[7]. On the one hand, it intends to apply the preliminary method to actual scars in order to extract a set of statistical parameters that describe their 3D topography.

Furthermore, the proposed method allows for the interpretation of extracted data as well as the establishment of direct correlations between data and clinical evaluation in order to objectively assess the scar's state of health and the efficacy of the therapy employed. It was possible to investigate a total of 9 case studies (4 of which came from previous investigations) thanks to the collaboration between DIEF and Meyer Children's Hospital burns department (T3ddy co-lab). The rest of the paper is as follows: Section 2 discusses the current techniques and methods for assessing scar health. Section 3 introduces the ISO standards, as well as the assessment methods for scar surface roughness and the significant parameters that we recommend considering. The application of our method for surface roughness is explained and applied to case studies in Section 4. Finally, the findings are examined, and a few suggestions are made.

2 SUBJECTIVE ASSESSMENT SCALE

The procedures employed to assess the condition of a burn scar remain unchanged since the early 2000s, and they do not provide for the possibility of getting an unambiguous and fully objective assessment of the scarred skin's state of health. The subjective rating scale is the most used ways for determining the status of a scar. Various types of assessment scales have been established over the years, all with the aim of assigning a numerical score to the wound by analyzing some of its features. The doctor sets a numerical value within a defined range (which changes depending on the scale) to each attribute evaluated to identify the state of that specific physical or mechanical property. When all critical criteria have been evaluated, the scores may be averaged to provide a burn scar healing index. Subjective assessment scales are always used to evaluate the features of a single patient's scar over time or after therapies, rather than to compare the characteristics of different patients. These scales are used to assess thin and linear scars, and, because of their low sensitivity, they can only identify large alterations between scars. The most critical fact is that different scars may be identified by the same score. They are also highly dependent on the user, the severity of the scars, and the age of the scar, and frequently require examination by numerous specialists (through using average value) to acquire valid and reliable information. No rating scale covers the whole variety of clinically relevant scar features, and most require two observers to get adequately reliable results. The last one restricts its application in practical practice.

The first scale to be established and still the most popular and widely used is the Vancouver Scar Scale (VSS). The physical factors considered have an effect on the scar's level of development and healing, appearance, and functionality. The Manchester Scar Scale (MSS) and the Patient and Observer Scar Assessment Scale (POSAS) are two more regularly used scales [2, 6]. The Manchester Scar Scale (MMS), the Patient and Observer Scar Assessment Scale (POSAS), and the Vancouver Scar Scale (VSS) are all characterized by low sensitivity and can only identify significant changes in the status of the same scar.

3 SURFACE TOPOLOGY CHARACTERIZATION

Surface topography measurement plays an important role in manufacturing, for both the control of manufacturing processes and for final product acceptance. [4]. The retrieval of representative surface parameters is essential to quantify the quality index of the component. To provide a precise technique for each component of surface roughness characterization, numerous standards were proposed over time. Table 1 shows the main standards used for the production process parameters and quality evaluation.

Thematic	*Profile method*	*Area method*
Surface texture parameters	ISO 4287:1997	ISO 25178:2
	ISO 13565:1996	
	ISO 12085:1996	
Measuring conditions	ISO 4288:1996	ISO 25178:3
	ISO 3274:1996	
Filter	ISO 11562:1996	Serie ISO 16610
Classification of measuring instruments	–	ISO25178-6:2010
Calibration of measuring instruments	ISO 12179:2000	under definition
Reference components for calibration	ISO 5436:1	ISO25178-70:2013
Graphic method	ISO 1302:2002	ISO25178-1:2016

Table 1: Main standards of profile and area methods.

Moving from the mechanical field to clinical applications, it is possible to transfer these concepts to the surface roughness of a scar, as this too may be interpreted as a surface "*defect*". To this aim, the paper proposed by "*Furferi et al.*" considered ISO standards by analyzing what approach were currently used in the mechanical field and on what methods they were based [9].

In detail, the parameters for calculating two-dimensional roughness according to ISO 4287 and ISO 4288 [8, 9] establish that any surface can be divided into three components called *shape*, *waviness,* and *roughness*. The definition of the precise threshold value for separating components is a subjective decision that is dependent on the field of application, because there is no reference standard. This means that the type of filter and the values used as cut-off wavelengths determine the roughness value. For this purpose, according to ISO 4287 [8], three types of filters are defined for profile analysis:

- λ_s filter: divides the roughness component from the shorter wave components,
- λ_c filter: divides the roughness component from the ripple components,
- λ_f filter: divides the waviness component from the longer wave components.

Profile filters are extended to areal filters in the ISO 25178-2 [12] standard as follows:

- *filter S:* areal Gaussian filters used to remove the short-wave component
- *operator F*: removes the nominal shape component of the surface
- *filter L:* for the larger scale wave component

The cutoff wavelength adopted for these operators is called the *'nesting index'*, according to the nomenclature introduced by the standard ISO 25178-2 [12].

In the case of topographical analysis of the scar surface, shape filters like second-order Gaussian regression filters (according to ISO 16610-1) can be applied to obtain better results [10].

The evaluation area is not constrained; in fact, in ISO 25178-2 [12] is only defined the shape of the evaluation area, which has to be square or rectangular.

3.1 Filtering Method Definition

The choice of filtering method is often arbitrary and affects the results, for this reason, it is important to select an adequate filter to observe and characterize only relevant components [15]. The ISO series of standards dealing with areal filters is part of ISO 16610 and extensively describes linear filtering strategies such as Gaussian, Spline and multiscale filters [10, 15].

In the ISO 16610-61 [11] is specified the metrological characteristics of the Gaussian areal filter. To compute the roughness of a surface, first apply the S-filter, then use the F-operator to produce the S-F surface, and then use the L-filter to generate the S-L surface, from which the roughness may be estimated. Figure 1 shows a diagram of this.

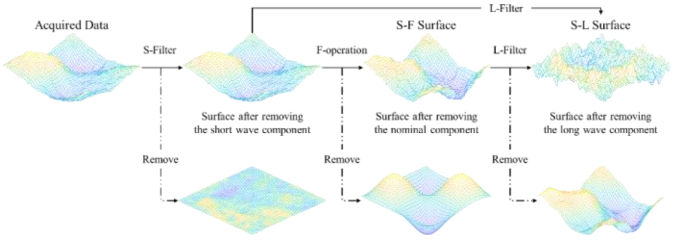


Figure 1: Implementation of Gaussian filter.

Among the latter, we can find wavelet-based filtering [1, 14, 17]. It can be decomposed and approached with a 1D method performing individually as row and column operations in an analogy to the 1D-DWT architecture [18]. As shown in Figure 2, by considering an image or surface of size n x n we derive, operating first along the rows with the execution of the filter function H(z), an n x n/2 matrix with the low-pass filter coefficients (L). In the same way with the execution of the filter function G(z) we obtain an n x n/2 matrix with the high-pass filtering coefficients (H). The same procedure is then applied to all the columns for each of the two matrices obtained. Bringing all four matrices together results in a matrix of four bands (LL, HL, LH, HH). Each band contains respectively the following properties:

- The LL band contains a coarse version of the image (longer wavelength).
- The HL band highlights discontinuities along the lines (short wavelength),
- the LH band highlights discontinuities along the columns (short wavelength),
- the HH band highlights discontinuities along the oblique direction (short wavelength).

As with the one-dimensional decomposition, the LL matrix can be decomposed into other sub-matrices up to the desired level.

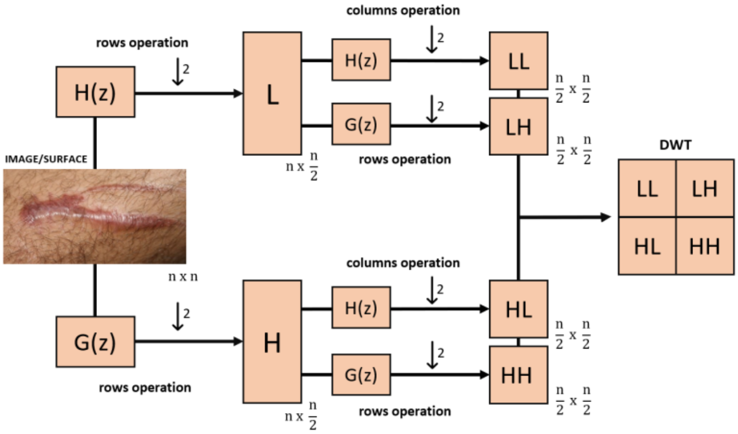


Figure 2: Implementation of 2D wavelets filter.

4 ROUGHNESS PARAMETER DEFINITION AND INTERPRETATION

The parameters for surface characterization are defined in ISO 25178-2 [12, 13]. As shown in [17], height parameters are the most used parameters, although spatial parameters can provide more information about the surface structure. The following parameters were considered for the characterization of the surface roughness of a burn scar:

- Sa = arithmetical mean of the absolute surface heights [mm]
- Sq = root mean square (rms) value of surface amplitudes [mm]
- Sp = the maximum peak height [mm]
- Sv = maximum valley depth [mm]
- Ssk (Skewness) = ratio of the average cube value of the surface ordinates to the cube of the Sq parameter [non-dimensional coefficient].
- Sku (Kurtosis) = ratio of the average quartic value of the surface ordinates to the fourth power of the Sq parameter [non-dimensional coefficient].

These parameters can be divided into absolute coefficients (Sa, Sq, Sp, Sv) and distribution coefficients (Ssk, Sku). Ssk value indicates the degree of symmetry of the surface heights about the means surface and it is close to 0 when there is an equilibrium between peaks and valleys. The sign indicates the predominance of peaks (Ssk >0) or valley (Ssk <0). Sku indicates the presence of inordinately high peaks/deep valleys (Sku >3.00) or lack thereof (Sku <3.00) making up the texture.

If the surface heights are normally distributed (i.e., bell curve) then Ssk is 0.00 and Sku is 3.00. Surfaces described as gradually varying, free of extreme peaks or valley features, will tend to have Sku <3.00. Ssk is useful in specifying honed surfaces and monitoring for different types of wear conditions. Sku is useful for indicating the presence of either peak or valley defects which may occur on a surface.

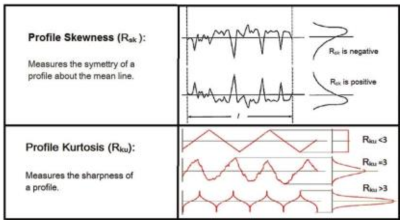


Figure 3: Interpretation of Skewness and Kurtosis for a 2D profile. In the 3D case they have the identical connotation but related to an area.

Analyzing the results provided by literature for a series of specimen tests, the capability of both implemented methods to consistently separate the contributions of roughness and shape under several reasonable assumptions can be confirmed [7].

From the analysis of the results obtained from the tests on a synthetic surface, it was possible to define both the optimal value of the Gaussian nesting index (equal to 2.5 mm) and the wavelet decomposition level (equal to 3). These values allowed a reliable identification of the roughness parameters in a range that can be considered a 'lower limit' for burn scars. By applying the method on ostrich skin [7], it was possible to assert that a variable nesting index in the range [10-15 mm] and a decomposition level greater than or equal to 6 are the most interesting to investigate for real scars. Starting from the assumptions made in [7], in this work a code is created in the MATLAB® environment to extract the surface roughness values of a scar using the Gauss and Wavelet filtering methods.

To investigate and demonstrate the viability of the proposed method, five study cases of patients in the Meyer pediatric hospital's burn department and four scars, previously used by the T3ddy co-lab for other purposes, were considered. The following section describes the methods and results obtained.

5 DATA ACQUISITION AND PROCESSING PROCEDURE AND RESULTS

The study was performed on burn scar patients, aged between 3 and 16 years old, referred to the burn's treatment department of the Meyer Children's Hospital. All patients agreed to participate in the study, with parental approval.

Scar scans were acquired with the *Artec Space Spider* 3D scanner produced by Artec3D. Scans were conducted at the Meyer Children's Hospital, under the supervision of the doctor, during a planned check-up visit. Table 2 contains the patients' data and the surgeon's clinical evaluation obtained from the visit.

	Burn cause	*Area*	*Burn Date*	*Type of operation*	*Pre-visit medical therapy*	*Scar type*	*Retraction*	*Post-visit medical therapy*

1	boiling liquid	3%	jen-22	grafting	splint, tensiogrip	hypertrophic	no	Cica-care
2	flame	50%	dec-20	escharectomy and dermabrasion followed by multiple grafts	splint, splint, tensiogrip, elastic sheaths, silicone patches, massage, FKT, a cycle of LPG	flat, hypertorphic right forearm and ear pinnae	no	Kenakort infiltrations
3	blaze	20%	aug-21	dermabrasion and advanced dressings (cuticel and aquacel)	Cica-care, massages, compression sleeve, Kenakort infiltrations	hypertrophic-kelloid with skin hyperemia (right hand)	no	Cica-care, a new cycle of Kenacort
4	/	/	2006	grafting	physiotherapy	hypertrophic	no	Plastic Z-surgery
5	gas cylinder explosion	9%	may - 19	escharctomy and grafting	elastic mask, silicone, gloves	flat scars	moderate joint retraction	massages

Table 2: Data from patients admitted to the Meyer Children's Hospital burns department.

The 3D scans have been elaborated by means of *Artec Studio* software package. Four of the five patients have a single burn scar, while patient 2 has 3 different scars on different body areas. Unfortunately, 3D data of patient 5 resulted unusable due to the fact the patient did not stand still during the scanning phase.

Patient	*Photo – Scan – 2.5 Mesh*
1	
2A	
2B	
2C	
3	

4	

Table 3: Photos, scans and 2.5D meshes of Meyer Hospital patients' scars.

The method implemented requires the scar in the form of a 2.5D mesh as input. To obtain an STL file of a 2.5D mesh to be inserted into the MATLAB® routine, post-processing operation on the scan were performed. In particular, the scan was cropped to a rectangular format centered on the scar. To obtain a 2.5D mesh, the 3D mesh is projected in 2D to a plane (in this case was considered the parallel plane to the patient's bed). Then the corresponding 2D points are triangulated and the mesh structure is applied to the 3D points. The resampling technique used to obtain a 2.5 D mesh is always susceptible to error, the size will depend on both the number of undercuts in the surface and of the resampling elements size. To minimize this error, the resampling value was set equal to the Artec Space Spider scanner resolution. The STL file in input for MATLAB® script must have a rectangular form for processing the information and performing the calculations considering it as a matrix of *n x m* elements.

Type	*INPUT*	*OUTPUT*
Gaussian Filtering	2,5D-STL scar surface file, sampling wavelengths (λ_s, λ_c, λ_f)	Sa, Sq, Sp, Sv, Ssk (Skewness), Sku (Kurtosis)
Wavelet Filtering	2,5D-STL scar surface file, decomposition level	Sa, Sq, Sp, Sv, Ssk (Skewness), Sku (Kurtosis)

Table 3: Input and output of MATLAB®® program for the two defined methods.

In order to provide the doctor more objective data on the scar, two different analyses were performed:

- Global scar surface roughness assessment
- Evaluation of the surface roughness by individual elements.

The addition of a second analysis model allows the doctor to monitor, over the course of the treatment sessions, not only the overall scar roughness but also a critical area's roughness.

5.1 Global Surface Roughness Evaluation

In this Section, the values of the roughness parameters of the entire scar are shown. Only the analysis process performed with the Gauss method is described to summarize the contents, however, the values obtained with both methods are reported. The procedure performed by the MATLAB® program is drafted in Figure 4.

To get a surface without scanning error, the S-filter is used to the pre-processed data. The L filter is next used, yielding the S-L surface, from which roughness data may be retrieved.

The *Surface-F*, in the case of a flat (non-hypertrophic) scar, represents the skin without a scar (healthy skin). This might be regarded as the form to which the scar evolves with therapy in the case of a hypertrophic scar. To clarify, a hypertrophic scar is a scar that grows above the level of healthy skin, entirely changing the morphology of the afflicted region.

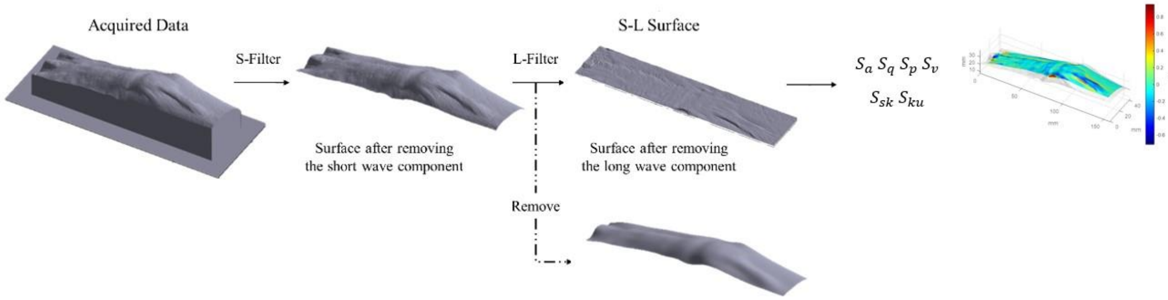


Figure 4: Graphical representation of roughness analysis process developed with MATLAB®.

In most situations, such scars have shapes and defects of the same size as the surrounding region. For this reason, when the two methods are applied, part of the scar is integrated into the "healthy skin". In this case, the Surface-F will represent a smoothing of the injured skin.

In the analysis of the roughness of hypertrophic scars there is therefore an evaluation against a "local standard" rather than a "fixed standard" (healthy skin) that is obtained at each new follow-up session.

To have a graphical display of the roughness, the difference between the scar without error and the F-surface was evaluated. The values of the scar roughness characterization parameters and the graphical representation are shown in Table 5 and in Figure 5. To increase the scars' dataset, four additional scars recently hired by the T3ddy co-lab for other studies have been also considered.

Scar	*Method*	*Sa [mm]*	*Sq [mm]*	*Sp [mm]*	*Sv [mm]*	*Ssk*	*Sku*
1	Gauss	0,10	0,13	0,67	0,44	0,39	4,49
	Wavelet	0,50	0,58	1,78	1,44	0,14	2,15
2A	Gauss	0,08	0,11	0,53	0,72	- 0,52	5,26
	Wavelet	0,27	0,34	1,16	1,53	- 0,16	3,50
2B	Gauss	0,06	0,08	0,39	0,55	- 0,31	5,70
	Wavelet	0,16	0,20	0,97	0,81	- 0,00	4,06
2C	Gauss	0,08	0,10	0,70	0,57	0,29	4,93
	Wavelet	0,17	0,22	1,40	0,85	0,55	5,01
3	Gauss	0,11	0,16	0,66	0,96	- 1,05	6,23
	Wavelet	0,42	0,53	2,21	2,18	- 0,05	3,05
4	Gauss	0,04	0,06	0,27	0,37	0,05	4,90
	Wavelet	0,19	0,25	0,99	0,75	0,48	3,36
5	Gauss	0,04	0,05	0,23	0,33	-0,45	5,16
	Wavelet	0,11	0,13	0,45	0,55	-0,00	2,97
6	Gauss	0,03	0,04	0,24	0,20	0,34	4,24
	Wavelet	0,12	0,16	0,90	0,55	0,76	5,40
7	Gauss	0,05	0,06	0,30	0,42	-0,50	5,51
	Wavelet	0,16	0,20	0,73	0,68	-0,03	3,06
8	Gauss	0,04	0,05	0,26	0,29	0,39	4,02
	Wavelet	0,12	0,18	0,93	0,67	0,95	6,14

Table 4: Output values of scar roughness and colour visualisation of the difference between the scarred and unscarred surface obtained by filtering with Gauss and Wavelet methods.

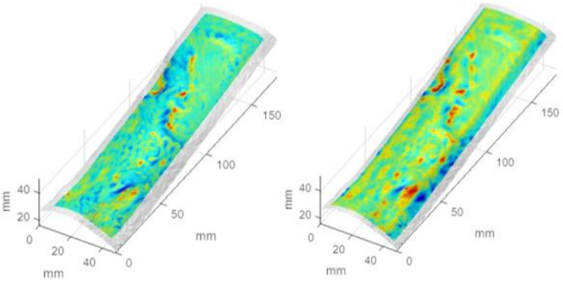


Figure 5: Illustration showing the differences between the scar surface and Surface-F. (a) Gaussian method, (b) Wavelet method.

It can be observed that the roughness values generated by the two approaches are comparable but not identical. According to the literature, the Gauss approach is more reliable and consistent than the Wavelet method [7]. For this reason, the latter method is used in this study.

5.2 Surface Roughness Evaluation by Individual Elements

The first analysis gives to the doctor information about general aspects of the scar. Instead, the doctor has the option to solely analyse the parameters for a small, crucial region by analyzing the roughness of each individual piece.

In this case, the MATLAB® program has a slightly different structure. The target area is cut out after the filter-s has been performed, and the S-L surface is obtained by subtracting the F-surface of the whole scar (this is to have the same F-surface as a reference for each individual element).

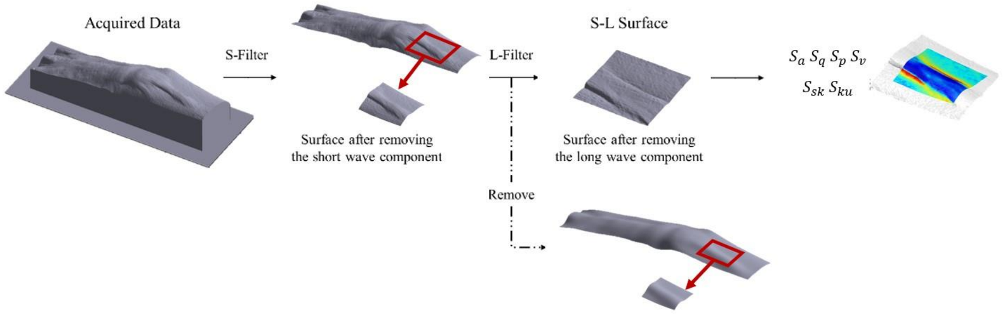


Figure 6: Graphical representation of roughness analysis process by individual element developed with MATLAB®.

By way of example, Table 6 lists the surface roughness values for a square element of dimensions 30mm x 30mm. The size of the element can be changed by adapting to the scar dimensions and to the doctor's request.

Method	*Sa [mm]*	*Sq [mm]*	*Sp [mm]*	*Sv [mm]*	*Ssk*	*Sku*
Gauss	0,20	0,24	0,45	0,75	-0,57	3,07

Table 6: Output values of scar roughness for an element of 30mm x 30mm.

Using standard measurements of the element, it is possible to divide the scan into square sub-scans to be analyzed individually. Figure 7 shows a possible configuration of the cutting array in square elements 30mm x 30mm.

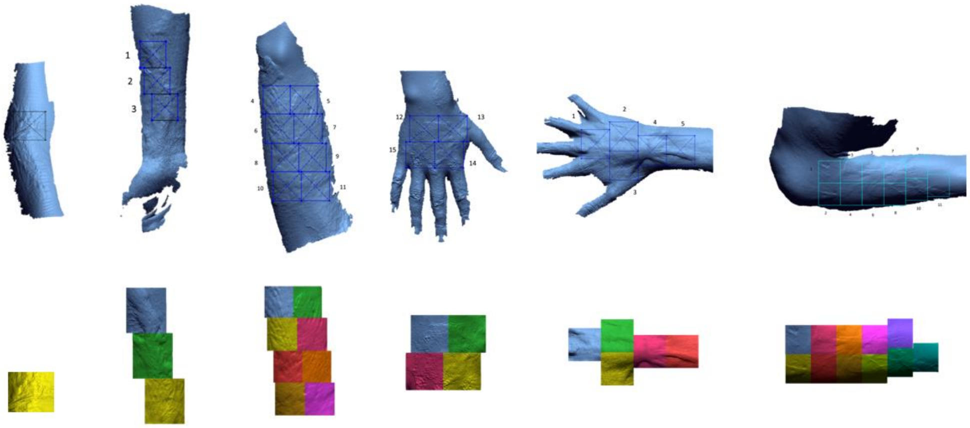


Figure 7: Scans division into multiple 300mm x 300mm square elements.

6 CONCLUSIONS

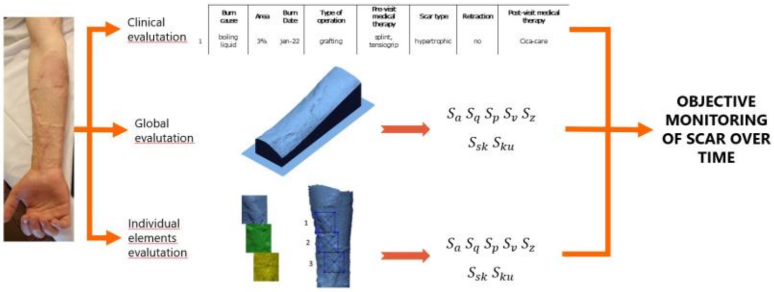
The implementation of an objective assessment system for surface roughness of burn scars would bring significant change in current clinical practices. Current methods for measuring this parameter are based on visual assessment and full dependency on subjective rating scales, i.e., the use of subjective approaches that do not allow for accurate and repeatable assessment.

The ambition of this work was to test the efficiency and reliability of the method, developed at a preliminary level in [7], by applying it on several patients of the Meyer Children's Hospital burns department. To achieve this goal, a program was developed in the MATLAB® environment that can calculate the roughness values of a burn scar by applying the filtering methods described in the ISO standards for mechanical surfaces [9, 10].

Two analyses were conducted in parallel to have an assessment of roughness both globally and by critical areas. Combining this information with the doctor's clinical evaluation provides an objective assessment for the health status of the scar. The parameters obtained should be compared with the parameters of a subsequent session after a treatment has been performed.

It is possible to say that the treatment is effective if the parameters overall decrease (in the case of Ssk (Skewness) and Sku (Kurtosis) if they are closer to 0 and 3, respectively). In addition, it is possible to understand the mutation of the scar by analyzing individual parameters and cross-referencing with another session. This has a significant benefit for scar management since it allows for the evaluation of the treatment's efficacy on both the entire scar and the area of concern. Figure 8 shows the parallel procedure of burn scar assessment; at the same time, a clinical assessment of the health status of the lesion can be performed by the physician and scanning can be carried out to proceed with global and detailed analysis.

Taking into consideration the absolute parameters derived from the application of Gaussian-based approach, it is possible to observe that for a hypertrophic scar the values are very similar to a flat scar even if they are completely different in shape. The reason may rely on the fact that the developed method evaluates the parameters having as reference the hypothetical shape of the scar after the treatment, that is the best result that can be obtained from the treatment. In particular, in the case of flat scars, the reference surface consists of the skin without scar, while in the case of hypertrophic scars an appropriately smoothed surface of the scar can be considered the ground truth.



	Burn cause	Area	Burn Date	Type of operation	Pre-visit medical therapy	Scar type	Retraction	Post-visit medical therapy
1	boiling liquid	3%	jan-22	grafting	splint, tensiogrip	hypertrophic	no	Cica-care

Figure 8: Data collection procedure for each control session.

The roughness values from the study above are comparable to and of the same size range as the values found in the literature. For this reason, the proposed method allows a coherent analysis of the scar surfaces. Moreover, it provides a set of statistical parameters, which mathematically describe the surface, in analogy to the study of mechanical surfaces. Accordingly, the proposed method is a first consistent step for the characterization of burn scars geometry. This work has the following limitation: to state that it is capable to ascertain if a therapy is working or not, it is required to have the data of a second follow-up visit of the same analysis scar. Therefore, future works will be addressed to a deeper investigation of this aspect, with particular reference to the study of the variation of the selected statistical parameters during the scar treatment. It is expected that for well-treated scars, where the appearance of the defect is also visually reduced, the roughness values identified with the proposed technique will tend to reduce the gap with respect to the ones evaluated on reference surfaces. This trend, however, is to be confirmed by further analysis.

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