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Evaluation of Wound Healing Process Based on Texture Analysis

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Abstract—**Wound healing rate, remains an interesting and important issue, in which modern imaging techniques have not yet given a definitive answer. In order to guide better therapeutic interventions, a better understanding of the fundamental mechanisms driving tissue repair are required. The wound healing rate is primarily quantified by the rate of change of the wound's surface area. The objective of this study was to establish a standardised and objective technique to asses the progress of wound healing in foot by means of texture analysis. The methods of image pre-processing, segmentation and texture analysis together with visual expert's evaluation were used to assess the wound healing process. A total of 40 digital images from ten different subjects with food wounds were taken every third day, for 12 days, by an inexpensive digital camera under variable lighting conditions. The images were intensity normalized, and wounds were automatic segmented using a snake's segmentation system. From the segmented wounds 15 different texture characteristics and 4 different geometrical features were extracted in order to identify features that quantify the rate of wound healing. We found texture characteristics that may indicate the progression of wound healing process. More specifically, some texture features increase (mean, contrast), while some other texture features decrease (entropy, sum of squares variance, sum average, sum variance) with the progression of the wound healing process. Some of these features were found to be significantly different in a specific time point and this could be used to indicate the rate of wound healing. No significant differences were found for all geometrical measures. The results of this study suggest that some texture features might be used to monitor the wound healing process, thus reducing the workload of experts, provide standardization, reduce costs, and improve the quality for patients. The simplicity of the method also suggests that it may be a valuable tool in clinical wound evaluation. Future work will incorporate additional texture and geometrical features for assessing the wound healing process in order to be used in the real clinical praxis.**

Keywords-Wound segmentation; texture analysis; wound healing rate.

I. INTRODUCTION

Chronic wounds present an increasing health challenge as the population ages and the incidence of different chronic diseases grows worldwide [1]. The progress of wound healing may be quantified by the rate of change of the wound's surface area [2]. However, this is a challenging task due to the complexity of the wound, the variable lighting conditions, and the time constraints in clinical laboratories. A color image of a wound on foot is presented in Fig. 1a). One way to evaluate wound healing rate is to monitor wound status by taking images of the wound at regular patient visits (see Fig. 2). If the physical dimensions of the wound are assessed at regular time intervals, then the experts will know if the patient is responding well or not to a particular treatment and if necessary change it [2]. In 2012 the 22nd annual meeting of the Wound Healing Society (WHS), set the standards for wound healing procedures and proposed recommendations for evaluating the optimal wound treatment [3].

There are not many research groups worldwide that are involved in color image processing of wounds. In [2], the authors proposed and evaluated an algorithm for the wound segmentation with minimal manual input and a high accuracy, which uses a combination of both RGB and L*a*b* color spaces, as well as a combination of threshold and pixel-based color comparing segmentation methods. Jones et al. [4], and Jones [5], developed the MAVIS system, which is able to automatically measure the dimensions of skin wounds. Their method was based on color segmentation algorithms and was able to segment an image into one of three tissue types: healthy skin, wound tissue and epithelialisation tissue. Furthermore, six measurement parameters: the R, G and B color planes, hue, saturation and gray-level intensity were taken into consideration. The R, G and B color planes were only examined in isolation showing that straightforward thresholding of color planes cannot produce a good segmentation which distinguishes between wound and skin tissues. They found that wound segmentation is only partially succeeded, if only the 1D color histograms were taken into consideration, while using a 3D RGB histogram space, the color volume clusters may be more widely separated and a better segmentation result can be achieved. Mekkes et al. [6], made some progress with such the 3D RGB color histogram clustering technique to asses the healing of wounds. It was shown that clusters in RGB space for a given tissue type formed an irregularly shaped 3D cloud, and so simple thresholding along the R, G and B axes would not help to segment the image into these three tissue types. Some other researchers presented their techniques on the segmentation of wounds in color mages based on the use of the black-yellow-red classification scheme to evaluate the debridement activity of wounds [7]. A method to correct for limb convexity in color video images in order to measure the size of skin wounds and

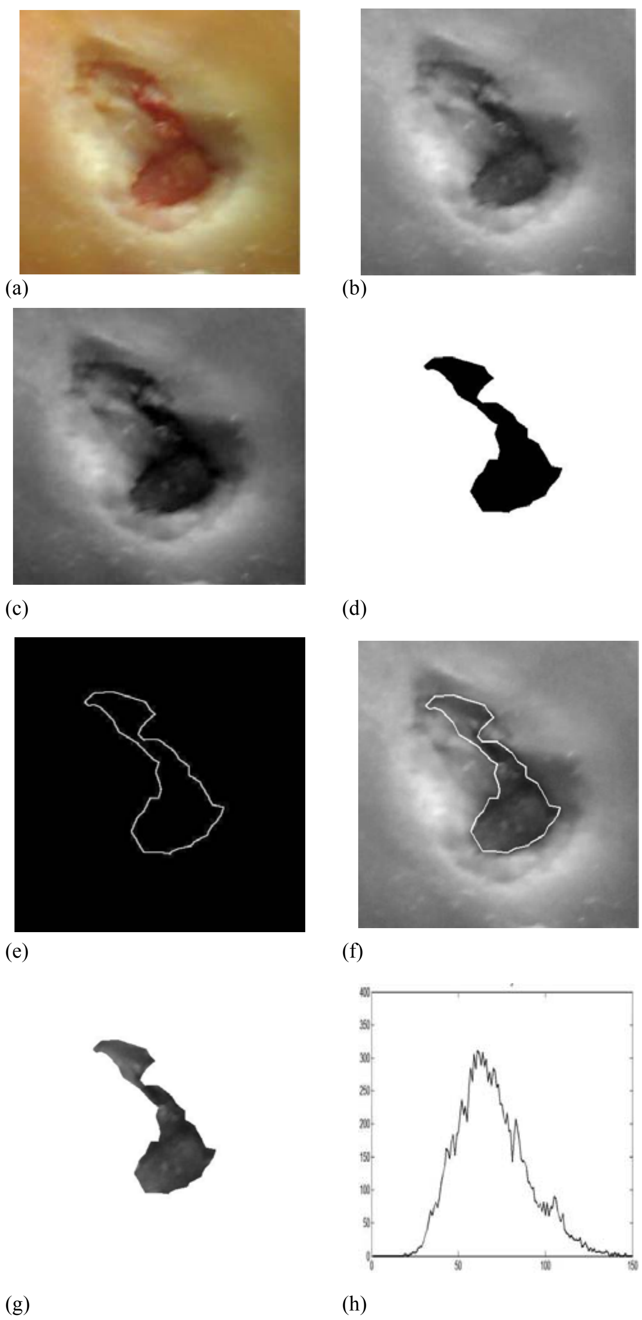

Figure 1. a) Original RGB color image of a wound on foot, from a patient at first visit, b) gray scale image of the wound, c) normalised image of the wound, d) binarised image of the wound, e) contour matrix of the binary wound image, f) final segmentation of the wound by snakes, g) segmented wound, f) histogram of the segmented wound.

ulceration was presented in [8], while techniques to evaluate wound repair in humans and animals using basic color image processing were proposed in [9]. In [10] a Support Vector Machine classifier (SVM) [11], was employed to perform region segmentation of the wound tissue followed by extraction of the wound contour. The authors in [10], used 50 RGB images manually delineated by experts as training data, and then tested their method using 23 new RGB wound images Their SVM algorithm was able to correctly classify roughly 94% of the pixels as either wound or non-wound, compared with professional tracings.

The objective of this study was to assess the progress of wound healing rate in foot wounds by means of texture analysis. Monitoring wound conditions over time is an important aspect of wound care, which is mainly nowadays carried out manually [2]-[7]. The development of a computer-based wound monitoring system will permit the definition of standard wound healing rates, minimize inter- and intra-observer variations, permit the electronic storage and retrieval of this information as a standard part of the patient's medical record. In this study we perform automated segmentation of the wounds based on snakes while the initial contour is automatically positioned to the area of interest. We follow up the rate of wound healing by means of texture futures and geometrical measures extracted from the automated segmented wound areas. The results of this study showed that there are texture features that may be used to monitor the rate of wound healing process.

The following section presents the materials and methods used in this study, whereas in section III, we present our results. Section IV and V give the discussion, and the concluding remarks respectively.

II. MATERIALS & METHODS

A. Acquisition of Wound Images

A total of 40 color digital images from 10 different patients with foot wounds were recorded (task carried out by the co author Michalis Poliviou, Podiatrist) and they were followed up every third day for 12 consecutive days. In each visit the wound was examined, and treatment was given. All patients were between 15 and 60 years of age, and had an ankle or foot wound with a minimum surface area of 1 cm^2. All patients received standard wound care, which included bi daily debridement, treatment with moist wound healing protocols, and offloading when appropriate. In some patients, active wound healing agents such as topical hydrogels, growth factors, and hyperbaric oxygen were used. Wound photographs were taken before wound debridement on each visit.

All wound images were taken, with a commercially available 8-bit Nikon D100 digital SLR camera with Canfield Twinflash illumination and polarizing filters (Nikon D100: Melville, NY). The polarized filters reduce light reflection from the wound surface and allow a better estimation of wound boundary. Images were taken in rooms with the lights shut off and the objects (wounds) were only illuminated by the flash light on the camera. Previous studies [12], have shown that the flashlight on the camera by itself is able to provide adequate illumination for surface wound images. Picture resolution was 538x695 pixels. All pictures were saved as JPEG files and ruler stickers placed in the imaging plane of the wounds were used as size references. A written informed consent was obtained from each patient according to the instructions of the local ethics committee.

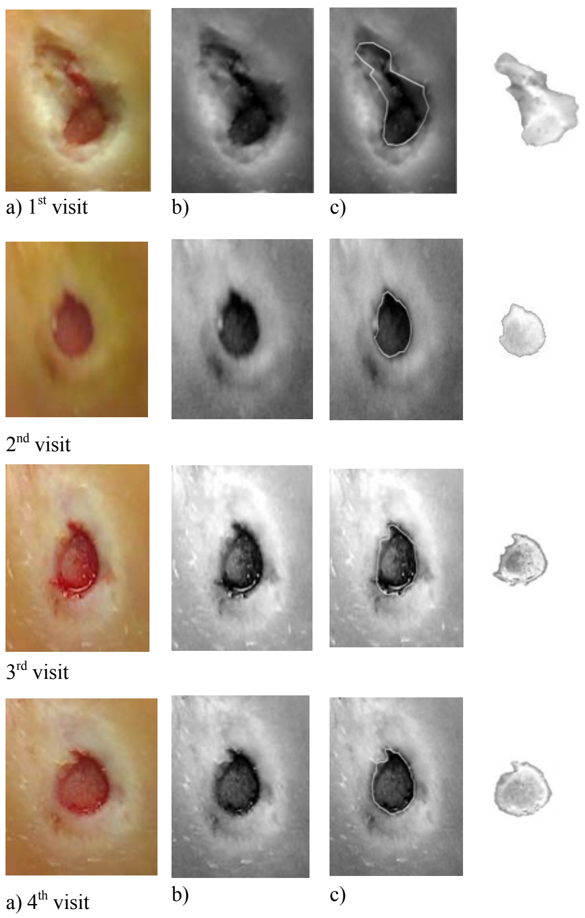

Figure 2. Original color wound image of the foot, from a patient at first visit (firt column), the corresponding gray normalised image (second column), the segmented wound (third column) and the extracted wound area (fourth column) for four concecutivew visits.

B. Image Intensity Normalisation

Brightness adjustments of wound images were carried out in this study based on the method introduced in [2], which improves image compatibility by reducing the variability introduced by different gain settings, different operators, different equipment, and facilitates image tissue comparability. The intensity normalization process was performed on the grayscale image (see Fig. 1b), which represents the first channel (luminance channel) of the original color wound image as follows:

$$N(i,j) = (I(i,j) - G_{\min})/(G_{\max} - G_{\min}) \qquad (1)$$

where $N(i,j)$ and $I(i,j)$ are the normalized and the original wound images respectively, $G_{\max}$ and $G_{\min}$ the maximum and the minimum grayscale values in the original grayscale wound image respectively [2]. The values, $G_{\max}$, $G_{\min}$, were manually selected by the user of the system. Thus the original image histogram was stretched, and shifted in order to cover all the gray scale levels in the image. The resulting wound normalized image is shown in Fig. 1c. The scale of the gray level of the images ranged from 0-255. Thus the brightness of all pixels in the image was readjusted according to the linear scale defined, by selecting the two reference regions ($G_{\max}$, $G_{\min}$).

C. Image Preprocessing

A wound initialization procedure was carried out for positioning the initial snake contour as close as possible to the area of interest. The procedure is described as follows (see Fig. 1): 1) Load the original color wound image (see Fig. 1a), 2) Compute and select the luminance channel of the image, which represent the grayscale image (see Fig. 1b), 3) Perform image intensity normalization (see section II.B). The normalized grayscale wound image is shown in Fig. 1c. 4) Binarise the image by image thresholding, in order to extract edges more easily (see Fig. 1d). A threshold is calculated from the normalized grayscale image according to [13] so that the intraclass variance of the thresholded black and white pixels is minimized. 5) Dilate the binary image (from step 4) by a 3x3 pixel-structuring element consisting of ones, which is multiplied with the binary image (see Fig 1d). This morphological operation is performed to close small gaps and form a continuous boundary. 6) Remove erroneous small edges that might trap the snake. This is carried out by labeling connecting components in the image where the number of connecting components in a pixel neighborhood was chosen to be eight. Small segments that are smaller than 20 pixels, and do not belong in the boundary are therefore removed. 7) Extract the contour matrix of the above area by locating points and their coordinates on wound boundaries, and construct an interpolating B-spline. Sample the interpolating B-spline, in equal distance points, in order to define a number of snake elements on the contour. The number of snake points was variable and was determined according to the area chosen by the user. The number of snake points was estimated by dividing the number of pixels belonging to the largest size of the area defined in Fig. 1d, by 20. This will affect that fewer or more snake points will be defined for a smaller or a larger area respectively. 8) Map the detected contour points from step 7, on the normalized wound image of Fig. 1c, to form the initial snake contour for the wound. 9) Apply the snakes segmentation algorithm [14] (see also section II.D) to extract and refine the final snake contours for the wound (see Fig. 1f). 10) Extract the area of the wound (see Fig. 1g) and draw its histogram (see Fig. 1h).

D. Snakes Segmentation

The Williams & Shah snake segmentation method [14] was used to deform the snake and segment the final wound borders as follows:

$$E_{snake}(v(s)) = E_{\text{int}}(v(s)) + E_{image}(v(s)) + E_{ext}(v(s)) = \int_s (\alpha(s)E_{cont} + \beta(s)E_{curv} + \gamma(s)E_{image} + E_{external})ds \qquad (2)$$

with $E_{\text{int}}(v)$ and $E_{ext}(v)$ the internal and the external energies of the snake. An additional image energy term, $E_{image}(v)$, which is given by the negative gradient of the current contour point proposed in [15]. For the calculation of the snake

TABLE I. MEAN VALUES ± STANDARD DEVIATION FOR TEXTURE FEATURES, THAT SHOWED SIGNIFICANCE BETWEEN CONSECUTIVE VISITS, EXTRACTED FROM ALL 10 PATIENTS, FROM ALL WOUNDS FOR FOLLOWING UP THE PROGRESSION OF WOUND HEALING. THE MANN WHITNEY RANK SUM TEST BETWEEN CONCECUTIVE VISITS WAS PERFOMRED AND THE P VALUE IS SHOWN UNDER EACH TEXTURE FEATURE IN PARENTHESES. ONLY SIGNIFICANDLY DIFFERENT FEATURES ARE SHOWN AT P<0.05. BOLDED VALUES INDIGATE SIGNIFICANLY DIFFERENT FEATURES.

	Visit 1	*Visit 2*	*Visit 3*	*Visit 4*
Mean	195±22	213±12 (0.24)	221±10 (0.37)	225±5 **(0.03)**
Contrast	90±40	120±50 (0.29)	160±80 (0.77)	180±50 **(0.02)**
Entropy	5.2±0.3	5.1±0.4 **(0.04)**	4.9±0.3 **(0.03)**	4.8±0.2 **(0.01)**
SSV	0.81±0.12	0.77±0.12 **(0.01)**	0.71±0.15 (0.04)	0.69±0.12 (0.34)
Sum Variance	449±14	434±15 (0.29)	418±26 (0.32)	401±43 **(0.02)**
Sum Average	0.07±0.03	0.06±0.03 **(0.02)**	0.05±0.03 (0.79)	0.04±0.03 (0.38)

SSV: Sum of squares variance

TABLE II. GEOMETRICAL MEASURES MEAN VALUES ± STANDARD DEVIATION, EXTRACTED FROM ALL 10 PATIENTS, FROM ALL WOUNDS FOR FOLLOWING UP THE PROGRESSION OF WOUND HEALING. MEASUREMENTS ARE IN PIXELS.

	Visit 1	*Visit 2*	*Visit 3*	*Visit 4*
Area	103±70	87±51	89±47	81±39
Perimeter	10320±1071	8890±8758	5474±5325	4399±3832
X-coordinate	4750±3561	4008±2650	3803±2636	2588±1595
Y-coordinate	109±64	95±50	86±34	78±31

parameters, $\alpha(s)$, and $\beta(s)$, we have chosen in our study the initial values of $\alpha_i(s)=0.6$, $\beta_i(s)=0.4$, and $\gamma_i(s)=2$, to start the snake deformation, which is consistent with other studies [14], [15]. The extracted final snake contours are shown in Fig. 1f (see also Fig. 2c). The proposed snakes segmentation method was proposed and evaluated in [15], in 100 ultrasound images of the common carotid artery (CCA) and more details about the model can be found there. The automated segmented wound boundaries were also visually assessed by a doctor, which confirmed the correct segmentation of the wounds.

E. Texture and Morphological Features

In this study the following texture features, and geometrical measures were extracted from all segmented wounds:

(i) Statistical Features (SF) [15], [16]*:* 1) Mean, 2) Standard Deviation, 3) Median value, 4) Skewness, 5) Kurtosis, and 7) Entropy.

(ii) Spatial Gray Level Dependence Matrices (SGLDM) as proposed by Haralick *et al*. [16]: 1) Contrast, 2) Sum of Squares Variance (SOSV), 3) Inverse Difference Moment (IDM), 4) Sum Average (SA), 5) Sum Variance (SV), 6) Sum Entropy (SE), 7) Entropy, 8) Difference Variance (DV), and 9) Difference Entropy (DE).

(iii) Geometrical measures: 1) Area, 2) Perimeter, 3) X-coordinate length, and 4) Y-coordinate length.

Each feature was computed using a distance of one pixel.

F. Statistical Analysis

As data were not normally distributed or had unequal variances, the Mann-Whitney rank sum test (for paired samples of different sizes), which calculates the difference between the sum of the ranks of two different independent samples, was used in order to identify if for each set of measurements a significant difference (S) or not (NS) exists between the texture features extracted from the wound images at different visits, with a confidence level of 95%. For significant differences, we require $p<0.05$.

III. RESULTS

Figure 2 illustrates an example of wound on foot, which shows the progression of wound healing in four consecutive visits (see 1st column in Fig. 2). In the second column of Fig. 2 we present the grayscale normalized image of the wound for the four visit points of the subject, while in the third column we provide the automated wound segmentations. Finally, in the last column of Fig. 2, we present the extracted wound areas after automated segmentation, for all four different visits.

Table I illustrates the mean ± standard deviation values for selected texture features extracted from the wound areas of all 10 subjects, that showed significant differences during the wound healing process. The Mann-Whitney rank sum test at $p<0.05$, was performed between consecutive visits in order to estimate significant differences between texture features. Some texture features increase (mean, contrast), while some other texture features decrease (entropy, SSV, SA, SV) with the progression of wound healing. The Mann Whitney rank sum test, showed different statistical significant differences for the texture features between consecutive visits. Texture features mean and contrast (see also Table I, with $p=0.03$ and $p=0.02$ respectively) showed an S after the 4th visit, texture features entropy, SSV and sum average (with $p=0.04$, $p=0.01$ and $p=0.02$ respectively) showed an S after the 2nd visit, while the texture feature sum variance ($p=0.02$) showed after the 4th visit a significant difference.

Table II illustrates the mean ± standard deviation of the geometrical measures, area, perimeter, x-coordinate length and y-coordinate length of all wounds and all patients, for four consecutive visits. It is shown that all four geometrical measures decrease with the progression of wound healing. The Mann Whitney rank sum test performed between the geometrical measures for all different visits, showed no significant differences.

Figure 3a) presents box plots for selected texture features, (mean (m) and sum variance (SV)), that showed singnificant differnce through the wound healing process, while Fig. 3b) illustrates the sum of squares variance (SSV) and the sum average (SA) for four concecutive visits (W1, W2, W3, W4). In each plot we display the median, lower, and upper quartiles and confidence interval around the median. Straight lines connect the nearest observations within 1.5 of the inter-quartile range (IQR) of the lower and upper quartiles. Unfilled triangles indicate possible outliers with values beyond the ends of the 1.5 x IQR. We obsereve that the texture feature median increases, while the texture features SV, SSV and SA decreases with the progression of wound healing.

IV. Discussion

The objective of this study was to establish texture and geometrical features, extracted in consecutive patient visits from foot wounds that may follow up the rate of wound healing. It is shown that it may be possible to follow up the progression of wound healing rate with the use of texture features extracted from the wound areas. We have followed up 10 different patients, from which 40 color images were acquired. The patients were presented with wounds on foot and were treated for four consecutive time points (visits), while digital images of the wounds were taken before treatment at each visit. The wounds were intensity normalized and automated segmented. Texture features and geometrical characteristics were extracted from the wounds in an attempt to find features that may describe the wound healing process. We found statistical significant differences between some of these features as follows: 1) The features mean and contrast, showed increase, and 2) The features entropy, SSV, sum variance and sum average, showed decrease with the progression of wound healing (see Table I and Fig. 3). Table I also some texture features can be used to follow up the progression of wound healing and it might be possible to estimate the time point in which the wound heals. Table II showed that the geometrical measures extracted from the wounds are not significantly different between consecutive visits thus they can possibly not be used for indicating the wound healing rate but they may be used for wound measurements.

We have found no other studies from the literature where texture features extracted from wounds, were used to monitor the progression of wound healing. There are some studies performed earlier by other researchers for measuring the wound size and in order to follow up the wound healing rate. In [18] two measuring methods, namely the acetate and planimetry are proposed against the manual measurement of wounds with the ruler. Accurate wound assessment and measurements are essential documentation parameters in the treatment of chronic and acute wounds. Changes in wound size and tissue type are key indicators in monitoring the healing progress of a wound [18]. Clinicians regularly face the complex tasks of choosing the appropriate treatment method and wound care product specific to the rate and points of healing.

In [12], two statistical measures, namely the kurtosis and the asymmetry, were extracted from 71 color images of burn wounds in order to classifying the deepness of the wound. They managed to classify the wounds with a classification success rate of 88.75% . In another study [20], the use of digital image processing using hue, saturation, and intensity measurements as a technique for the color analysis of chronic wounds on the skin was presented. An adaptive spline technique was used to segment the wound boundary in the images of venous leg ulcers. The technique was further used to approximate the position of venous leg ulcers. The amount of slough within the wound site was quantified using the software developed and was compared with a grading system based on visual inspection by an experienced clinician, and the results

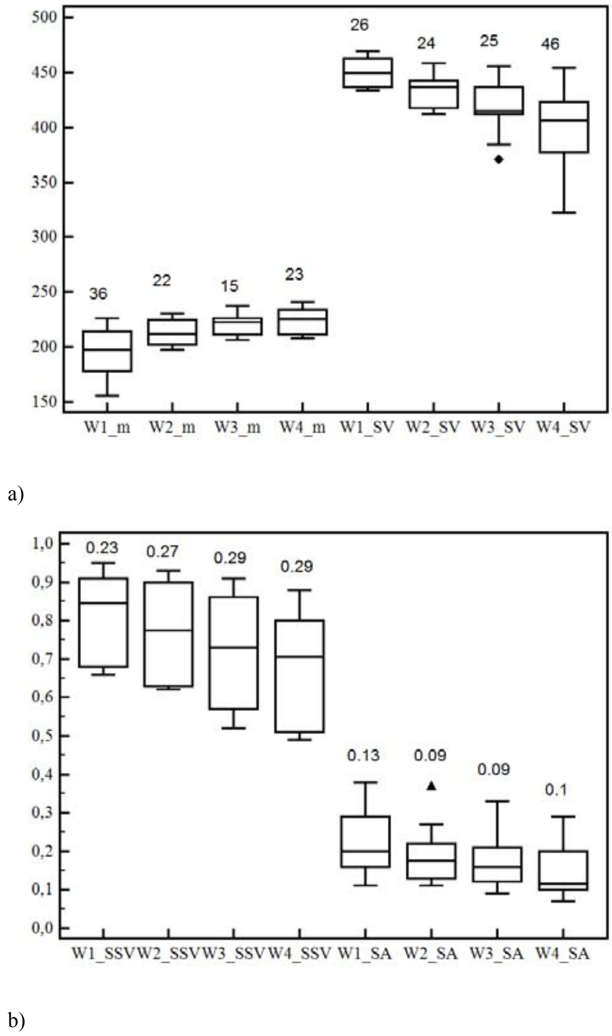

Figure 3. Box plots for wound texture features from all patients a) mean (m) and sum variance (SV), b) sum of squares variance (SSV) and sum average (SA) for four concecutive patient visits (W1, W2, W3, W4). In each plot we display the median, lower, and upper quartiles and confidence interval around the median. Straight lines connect the nearest observations within 1.5 of the IQR of the lower and upper quartiles. Unfilled triangles indicate possible outliers with values beyond the ends of the 1.5 x IQR.

were compared by deriving Kappa statistic. There was moderate agreement over all grades between the computer and clinician. At lower grades 1 and 2, there was excellent agreement. The results from this preliminary study suggest that this analytical technique has the potential to image process chronic skin wounds.

Flanagan [19], suggested an advantage of wound size monitoring is that plotting healing rates against initial wound area and then comparing them with a defined standard helps to inform clinical decision-making and reduces the likelihood of ineffective treatments. Eventually, this information may help in establishing baseline healing rates for different wound types, which would facilitate meta-analysis, allow objective comparisons of different treatments and assist reliable cost-benefit analysis [19]. It was also reported in [19], that nurses often report on the type of tissue found in the wound bed and use this as an indicator of progress towards healing. The analysis of wound tissue is a key parameter required in understanding exactly what is happening within the wound bed and whether the current treatment method is improving the wound healing process.

The initialization of the contour as presented in this study, poses a certain limitation of the method. If the initial contour for the wound is placed far away from the correct boundary then the snake contour will end up in a wrong location. Therefore, a more robust initialization method should be in future investigated. Another limitation of the method is that manual segmentations of the wounds were not performed by expert/s. In such a case, the automated segmented wound boundaries could be compared with the manual segmented boundaries and the method would be therefore correctly evaluated. Another limitation is the small number of images, in which the current method was applied. A further limitation is that all different types of wounds, of different initial size and of various tissue types are here collectively treated. By treating them as a single group individual differences are masked. This is evident in Table II. We intent to tackle this issue appropriately when more images are acquired. We are currently collecting additional images and we intent to perform the study on a larger number of images in order to validate the results of this study.

V. Concluding Remarks

This paper presents a study on the evaluation of wound healing rate based on texture analysis. The results of the study showed that it may be possible to follow up the degree of the wound healing rate by means of texture analysis. This will probably give an additional tool to the examining specialist for deciding on the correct treatment of the wound.

Further research work on a larger number of subjects is required for validating the results of this study and for finding additional texture and shape features that may provide information for longitudinal monitoring of the wound healing of subjects with wounds. The proposed system will be further evaluated on a larger sample of images as well as incorporate other texture features and measures which may quantify the rate of wound healing. The development of such a system will permit the definition of standard wound healing rates, minimize inter- and intra-observer variations, and permit the electronic storage and retrieval of this information as a standard part of the patient's medical record. We anticipate that the proposed system may be incorporate in the clinical praxis in an attempt to assist health care professionals, such as dermatologists, podiatrists and nurses, for more accurate diagnosis and treatment of wounds. We also believe that the above study may have some clinical value in following up the progression of the wound.

The proposed methodology may also be applied in the estimation of deep wounds, which is a major challenge. This kind of wounds has very small surface areas where color-based detection can lead to erroneous results and which could be overcome by texture-based detection methods.

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