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PAPER

Methodology for Monitoring and Control of Finger Deformation in Patients with Arthritis Using Fractal Dimension

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ABSTRACT

Regenerative diseases, as is the case of arthritis, generate a change in the morphology of the fingers and toes; thus, as time passes, the joints of the fingers begin to deform, which causes a change in the morphology of the joints and fingers. One of the effects that is noticeable by patients is the pain that these deformations cause in addition to the deterioration of the maneuverability of objects with hands. In this article we present a method for the analysis of the fingers of the hands, through the analysis of images obtained through the photographic registration of the hand, then the value of the fractal dimension (FD) is obtained, to know the objective index for the measurement of the morphology of the hand, in this way it is possible to evaluate the deformation of the joints of the fingers, In this way it is possible to analyze and monitor the level of deformation, thus being able to improve the treatment. Due to having a record of the evolution of the deformations, we present as a result a demonstration of the methodology by analyzing the FD of the hands of a patient. The calculation of the FD was developed using the Matlab tool, which can be replicated and scaled according to the need of each situation.

KEYWORDS

image, fractal dimension (FD), calculation, arthritis, monitoring

1 INTRODUCTION

Performing the review of the state of the art, we found works where the fractal dimension (FD) technique is exploited; the use of the FD in the health area, we find as works where they focus on the analysis of morphological complexity in biological systems, being considered as a quantitative parameter in the context of cerebral vascular complexity. Fractal analysis allows the detection of cerebral arteriovenous malformations in magnetic resonance images by calculating

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the FD using the box-counting technique [1]. We found related work on the use of high-resolution three-dimensional fractal geometry to study subtle and potentially biologically relevant structural alterations in the subcortical gray matter of schizophrenia patients relative to healthy individuals. In particular, we focus on the use of FD in high-resolution magnetic resonance imaging in chronic patients with schizophrenia [2]. The actin cytoskeleton is indispensable for the motility and migration of all cell types; therefore, it plays a crucial role in tissue repair capacity. Mesenchymal stem cells: this technique is continuously used in regenerative medicine, where a quantitative estimation is required, using microscopy techniques, in order to quantify cell reorganization measured by FD using the box-counting method [3].

The relationship between the chaotic component of photoplethysmography and hemodynamic parameters was analyzed, using the WK4 model to explore this association. Complexity measures such as FD were evaluated, and significant correlations with hemodynamic condition were identified, suggesting the importance of these measures in estimating hemodynamics. Furthermore, the need to investigate the interactions between hemodynamic fluctuation and temporal fractality was highlighted, proposing in silico simulations and additional quantitative analyses to improve hemodynamic estimation in different age groups [4].

Artificial intelligence is used in medical image analysis, especially in CT lung imaging to detect the SARS-CoV-2 virus. The use of convolutional and recurrent neural networks is highlighted to achieve a maximum accuracy of 98.1% in virus detection. In addition, fractal analysis is explored as a tool to characterize the evolution of COVID-19 infection and prescribe optimal treatments. The importance of artificial intelligence in medical care is highlighted, showing how technology can improve accuracy in the diagnosis and monitoring of diseases. The relevance of fractal theory in the evaluation of experimental data is mentioned, such as the determination of FD and other fractal features in medical images [5].

Fractal analysis in lung CT images of patients with COVID-19, evaluating fractal and lacunarity dimensions. 3D graphic representations of the lungs were presented, and fractality and lacunarity values were compared between affected patients and controls. The importance of low-dose computed tomography for evaluating lung lesions in COVID-19 was highlighted in the study [6].

The usefulness of FD analysis to distinguish between oral squamous cell carcinoma (OSCC) and healthy oral mucosa. A significant difference in FD was observed between the OSCC and normal groups, indicating greater structural complexity in OSCC tissues. This innovative computational tool shows promise in the early detection of oral cancer, which could improve patient outcomes and reduce mortality rates associated with oral squamous cell carcinoma [7].

The relationship between the FD of the sEMG signal and motor unit timing and firing frequency in 13 healthy subjects. Results showed a significant decline in maximal voluntary force during isometric knee flexion, with FD of the sEMG signal correlated with motor unit synchronization and firing frequency. The methodology included analysis of individual motor units and decomposition of iEMG signals, concluding that FD of the sEMG signal is related to motor unit synchronization and firing frequency and that changes in the sEMG signal are associated with central factors rather than muscle fiber conduction velocity [8].

The reduction of the brain fractal coefficient in Alzheimer's disease (AD) and its relationship with other diseases such as multiple sclerosis (MS) and spinocerebellar ataxia (SCA). The use of the fractal coefficient (FD) to assess the complexity of biological structures at different scales is highlighted, although the correlation with underlying biological changes is still unclear. The need for correlations with validated biomarkers to better understand the value of FD in the characterization of neurodegenerative diseases is highlighted [9].

The relationship between left ventricular FD and clinical outcomes in patients with dilated cardiomyopathy. We found that the maximum apical left ventricular FD was an independent predictor of adverse events, offering additional prognostic value over conventional risk factors. Furthermore, left ventricular trabecular complexity was associated with adverse cardiac events in this patient population, suggesting that FD analysis could improve risk stratification and guide treatment in patients with dilated cardiomyopathy. This study highlighted the importance of FD as a noninvasive tool to assess prognosis in patients with DCM. It was concluded that the maximum apical FD of the left ventricle was a significant predictor of adverse clinical outcomes, suggesting its usefulness in clinical practice to improve risk stratification and guide treatment decisions in patients with dilated cardiomyopathy [10].

The relationship between retinal vascular complexity and cognitive function in older adults during a two-year follow-up. We found that decreased retinal vascular complexity was associated with poor performance in attention and memory, especially on the right side. Despite finding no significant associations with global cognitive decline, low retinal vascular complexity was associated with poorer performance in attention and memory over time, suggesting a possible link between vascular health and cognitive function in older adults [11].

Fractal geometry of the brain in patients with MS; a significant decrease in white and gray matter FD was observed, along with an increase in cortical and white and gray matter lacunarity. Furthermore, a correlation was found between the cortical FD and cumulative disability in these patients. These findings suggest that the brain FD could be a useful biomarker for monitoring brain damage in individuals with multiple sclerosis [12].

COVID-19 propagation using fractal interpolation and FD. It is proposed to reconstruct epidemic curves from a fractal perspective to predict disease evolution and compensate for the lack of evidence. The complexity of virus spread is highlighted, and the importance of understanding the connections between infection clusters to model future epidemics more effectively is discussed [13].

The relationship between the D FD of lung slices and the initiation of long-term oxygen therapy (LTOT) in patients with COPD. A stronger correlation was observed between fractal D and LTOT than with the percentage of low attenuation areas (LAA%). In addition, common predictive factors were identified in the Nara Medical University and Kyoto University cohorts, including DLCO, %DLCO, LAA%, and fractal D as indicators associated with LTOT. This study highlights the importance of D fractal as a potential predictor of the need for LTOT in patients with COPD, demonstrating consistency in predictive factors among the cohorts studied. These findings suggest that assessment of the D FD in lung slices could be useful in the early identification of COPD patients who may require long-term oxygen therapy [14].

Fractal dimension descriptors on retinal images to facilitate patient identification and pathology tracking. These descriptors are organized in a tree data structure to streamline image search and comparison, significantly reducing database search time. The elimination of frequent descriptors helps to speed up the search process and improve the accuracy in retrieving images related to the same patient, which can be crucial in clinical monitoring and diagnostic applications in ophthalmology [15].

We found works where respiratory diseases caused by viruses such as pneumonia are analyzed, applied to x-ray images taken in children, and four convolutional neural network models (VGG16, VGG19, ResNet50, and InceptionV3) are analyzed. These were evaluated by analyzing the precision; in the analysis, the InceptionV3 model achieved the best performance with 72.9% precision, concluding that CNN models are suitable for detecting pneumonia due to their high precision. Continuing the analysis of respiratory diseases, we find works that focus on the analysis of disease data, using data mining, analyzing 10,000 Peruvian clinical histories from the last 5 years, and obtaining different behaviors through the use of techniques such as grouping, which allows helping health centers in Peru with their subsequent analysis and decision-making for prevention policies towards respiratory diseases [16, 17].

In this study, we perform an analysis of images recorded of people with arthritis in order to determine the behavior through the analysis of the FD, represented in the palm of the hands, characterized by the alterations or deformations of the fingers and toes, a product of arthritis. With which we can indicate that arthritis is a degenerative disease that mainly attacks the joints of the fingers and toes, causing changes in the shape of the fingers consecutively. The presented method allows to measure and evaluate the situation of the shape of the fingers and hands through image processing and calculation of the FD. In order to know the state and evolution of the deformations, a change in the FD allows us to determine a change in the shape of the fingers and therefore a variation in the normal shape of the fingers and hands.

2 MATERIALS AND METHODS

The materials and methods are related to the description of the proposed methodology, where we explain from the description of the problem related to the problems of patients suffering from arthritis, which is evidenced by the deformation of the joints of the fingers, then we present the description of the proposed method and end with the calculation of the fractal dimension.

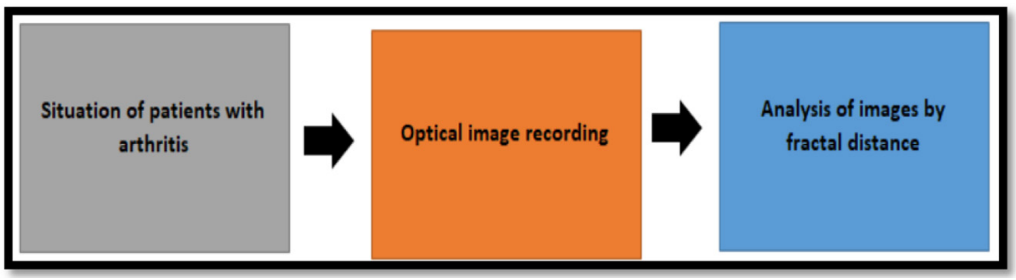


Fig. 1. Description of the proposed methodology

Figure 1 shows the block diagram of the procedures necessary to describe the proposed methodology, starting with the description of the problem, followed by the steps necessary to process the images, and ending with the calculation of the fractal dimension.

2.1 Situation of patients with arthritis

The problem presented is related to the morphological deformation of the fingers, which develops in patients diagnosed with arthritis; this disease preferentially attacks the joints of the fingers and toes. These deformations cause a change in the morphology of the fingers in their structural form and in the biophysics of the movement of the hands and feet. This disease has no cure, so most of the treatments are related to controlling the deformation. One of the techniques used by doctors is the visual analysis to indicate the level of deformation that patients have, which resorts to subjective methods to determine the level of deformation or change in morphology that are suffering the fingers.

2.2 Optical image recording

The methodology presented has a strong component in the processing of the images recorded in the patient, as well as the processing required to obtain the FD, which is the objective factor to determine the degree of deformation that may present the hands or feet, for our case to demonstrate the methodology a demonstration is made with the analysis of the hands, which are indicated below:

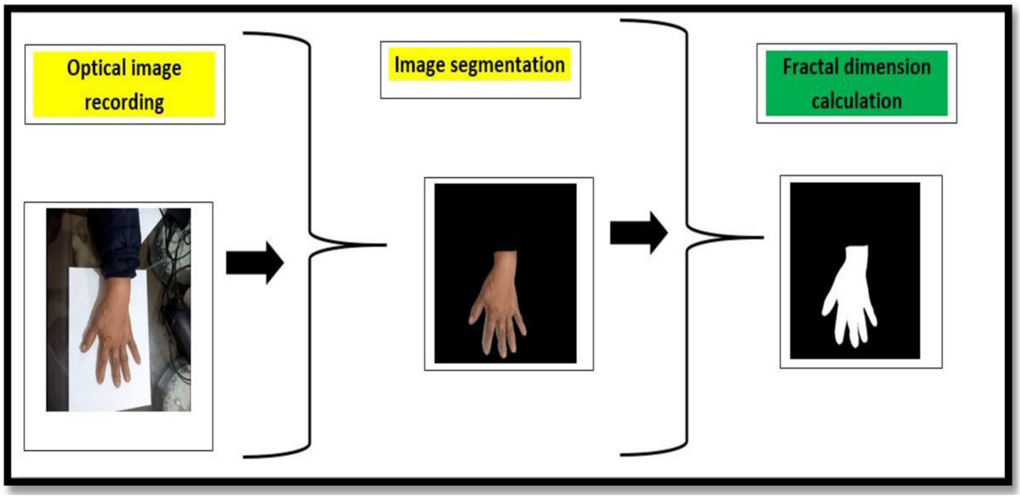


Fig. 2. Steps for image processing

Figure 2 shows the steps to calculate the FD, starting with the registration of the hand image, followed by the result of the image preprocessing, which is the elimination of the background image, and ending with the obtaining of the hand mask, which must be binarized to calculate the fractal dimension.

The first step is the registration of the patient's image, which can be done by different procedures, from the use of high-resolution cameras to the use of cameras found in cellular devices. The objective of the image is to capture the contour of the hand but not the detail. For the demonstration of the method, the registration was performed using a white background image to calculate the edges of the hand in a more optimal way. The image can be stored in any format, such as JPG, PNG, BMP, and others.

The second step is related to the pre-processing of the image, which consists in the elimination of the image from the background. This procedure can be performed automatically by using image processing techniques; alternatively, the image can also be pre-processed manually using different programs such as Paint, among others. Depending on the type of image registration, the result of this step is to have the image of the hand with a uniform background, which will serve as the input image for the next step.

The third step is related to obtaining the image mask, having as input image the image with the standardized background. In order to obtain the image that corresponds to the mask, image processing techniques such as edge detection techniques, it can also be done using manual techniques, the intention of having as a result the image of the hand mask, is to be used as input for the calculation of the FD, the format of the resulting image of the hand mask can be in JPG, PNG, BMP and others.

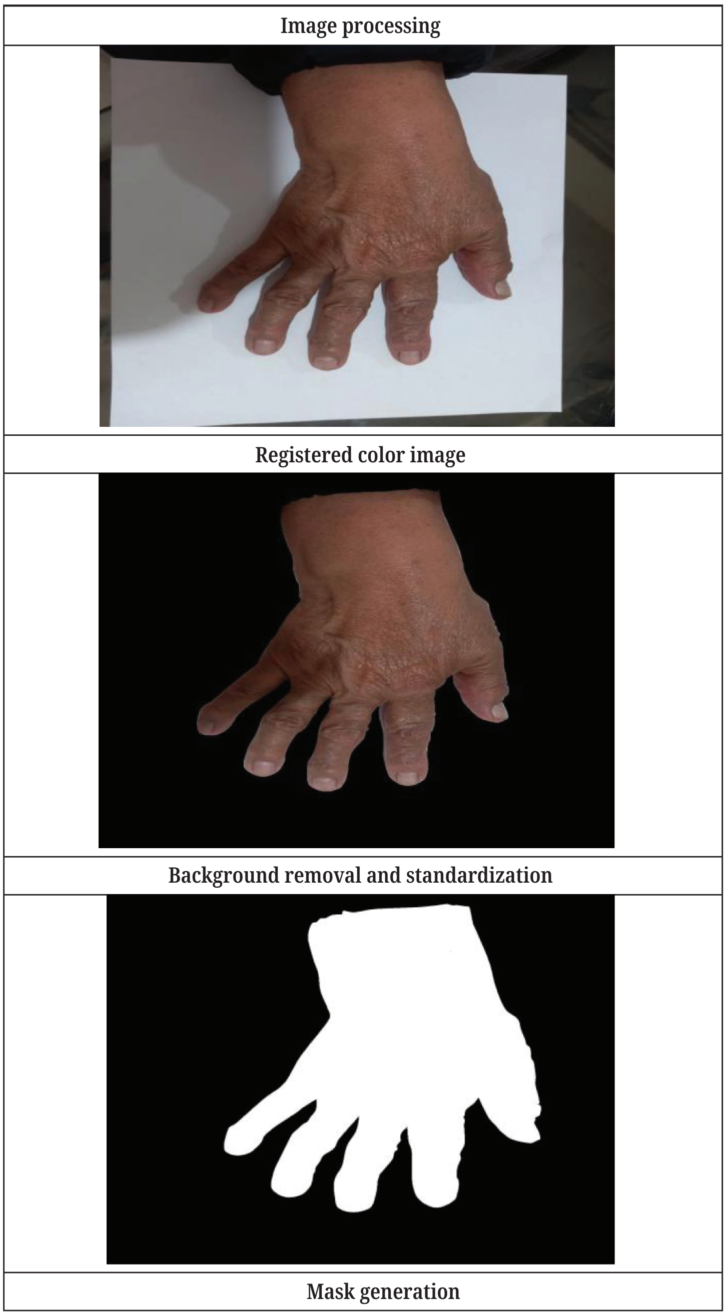


Fig. 3. Image processing for mask production

Figure 3 shows the images resulting from the image processing, starting from the registration of the color image, to obtain the mask of the hand, which is the image of the hand in white and the background in black. This process can be performed using the binarization technique.

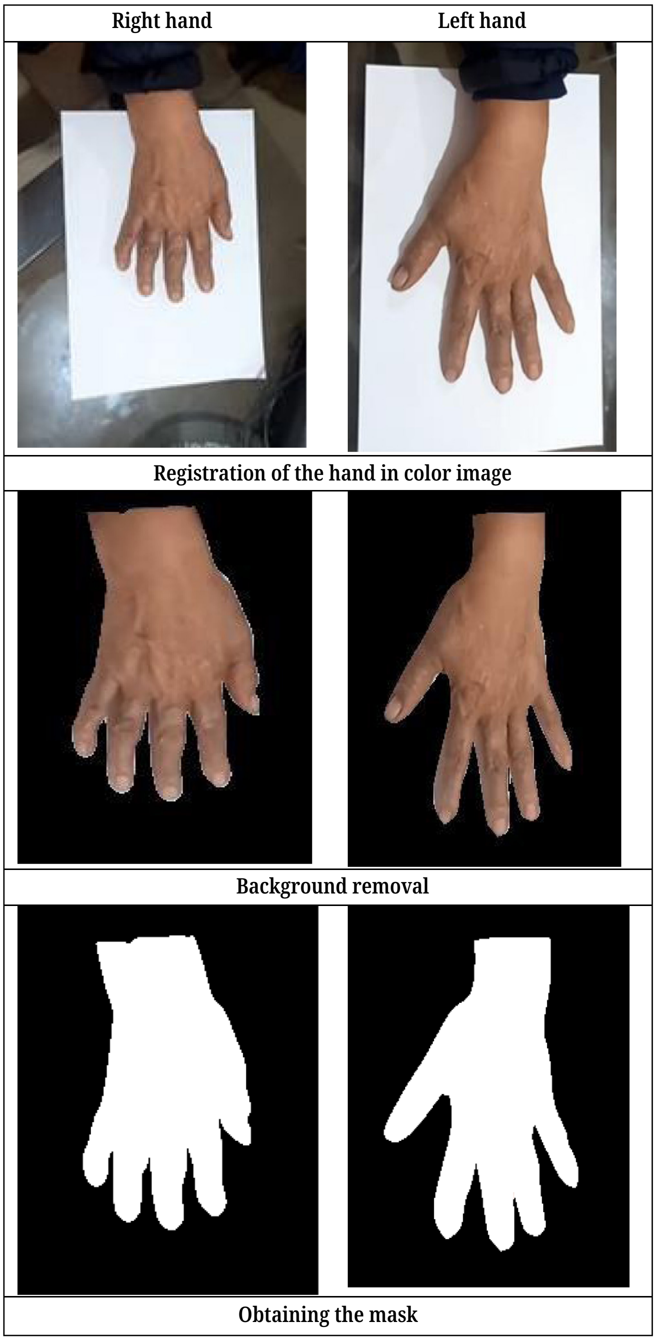


Fig. 4. Image processing for mask production

Figure 4 shows the processing of the images for the analysis of both hands, where the input image is the image of both color images. The processing and analysis are performed independently for each hand, obtaining as a final result two images that correspond to the masks of each hand. For each of the images, the FD will be calculated.

2.3 Analysis of images by fractal distance

Having as the final image the mask image, in the image processing stage, the next step is the calculation of the FD, by using the box counting technique, for which an

Algorithm 1 implemented with the Matlab tool has been implemented. The technique has two steps: the first one consists of converting the mask image that is in color format, which consists of having the three color bands, to a binarized image to obtain a single band or a single matrix. From the binarized image, we proceed to detect the edges of the images in order to perform the calculation of the FD, as shown in Figure 5.

Algorithm 1: Pseudocode of the Algorithm

Below we present the pseudocode for the FD calculation:

```
1. Input of an image of the object to calculate the fractal dimension.
2. Binarize the image.
3. We find the edges of the image.
4. We find the value of the columns and rows of the image.
5. We generate a new image with white pixels with the size of the original image.
6. We count the number of white pixels.
7. If pixel in (row, column) is white then
           white_pixel [row][column] = 1
8. Initialize the non-empty boxes counter
   non-empty_boxes = 0
9. Scroll the image and count non-empty boxes.
10. For each "row_start" in "0" up to "rows-box_size" with steps "box_size":
    For each "start_column" in "0" up to "columns-box_size" with steps "box_size":
11. We check if the box contains at least one white pixel.
       "box_not_empty" = False.
       For each row in "row_start" up to "row_start+box_size-1":
         For each column in "start_column" through "start_column+box_size-1":
           If "white_pixels"[row][column] == 1 then.
             "non-empty_box" = True.
             Break loop.
       If "non-empty_box" == True then.
         non-empty_boxes + = 1
12. Calculate fractal dimension
    "fractal_dimension" = Log ("non-empty_boxes") / Log(1 / "box_size")
13. Return the "fractal_dimension".
```

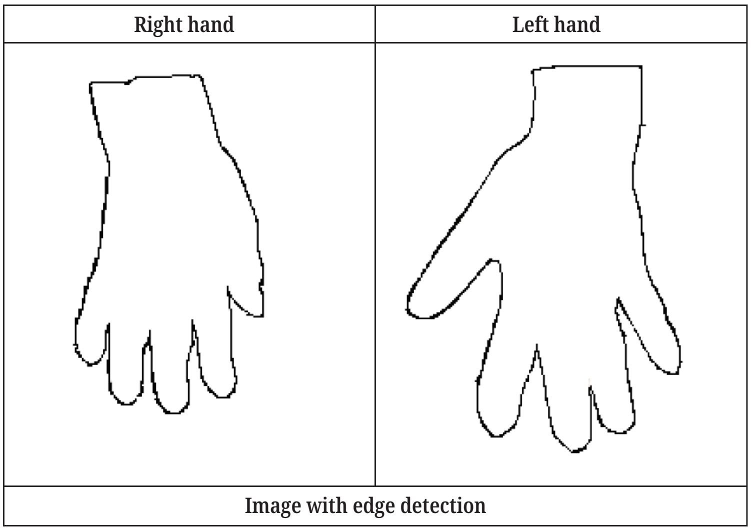


Fig. 5. Image processing with edge detection

Figure 5 shows one of the first processes of the pseudocode, for the calculation of the FD, where the patient's hand is represented with the identification of the edges, both hands are shown because we will perform the analysis of both hands.

3 RESULTS

The results that we present are related to showing the results after the experimentation, focusing on the calculation of the FD of the patient's hands, analyzing through the registration of the color image to the calculation of the FD of each hand, then we indicate the results obtained in each process.

Figure 6 shows the different processes that we can find in the development of the methodology. From the beginning with the registration of the image by using a camera that is on mobile devices, for the registration of both images that correspond to the hands, we work with the same camera and perform the registration at the same distance. With the obtaining of the image, we proceed to perform the processing of the images, where we eliminate the background image, and then we perform the binarization of the image, where the image corresponding to the hand is identified with white pixels and black background.

After the binarization of the image, we perform the process of calculating the FD, for which we perform an implementation using the Matlab tool, for which it is required to convert the image into a single matrix and perform the process of locating the edges, which is why the final image is a bank color image with black edges that correspond to the edges of the hand.

Through the implementation of the pseudocode in Matlab, the value of the FD is calculated for both hands, using the box counting method, for which the FD value of 1.1738 was obtained for the right hand and the FD value of 1.2040 for the left hand, with which we can indicate that each of the hands presents different values for the FD, with which each of the hands can be monitored independently, always following the same protocol of use of the methodology, which is described below.

The protocol for the use and application of the methodology is described in Figure 7, where it is indicated in the form of a flow chart, where each of the main tasks is identified starting with the registration of the image and the processes of background elimination to edge detection. It is at this stage where the question is asked if the image that corresponds to the edges has all the delimitation of the edges; if it is identified that there are areas where there is no presence of edges, the image is rejected and the image is re-registered. This stage is considered important because we require a level of edge detail, always looking for the closest possible; in the case presented, the edge of the hands. Otherwise, if we do not consider a good delimitation of the edges, we run the risk of obtaining a value with errors when calculating the fractal dimension.

Another very important consideration that we must consider in order to eliminate any error in the use of the methodology is related to the use of the same camera and performing the registration with the same focal length, so as to have the same size of the image at the time of registration and always have a standard size of the image because the calculation of the FD is performed considering each of the pixels, so for all images to be analyzed at the time of comparisons and evolutions of the degree of deformity, we must consider that the images have the same size.

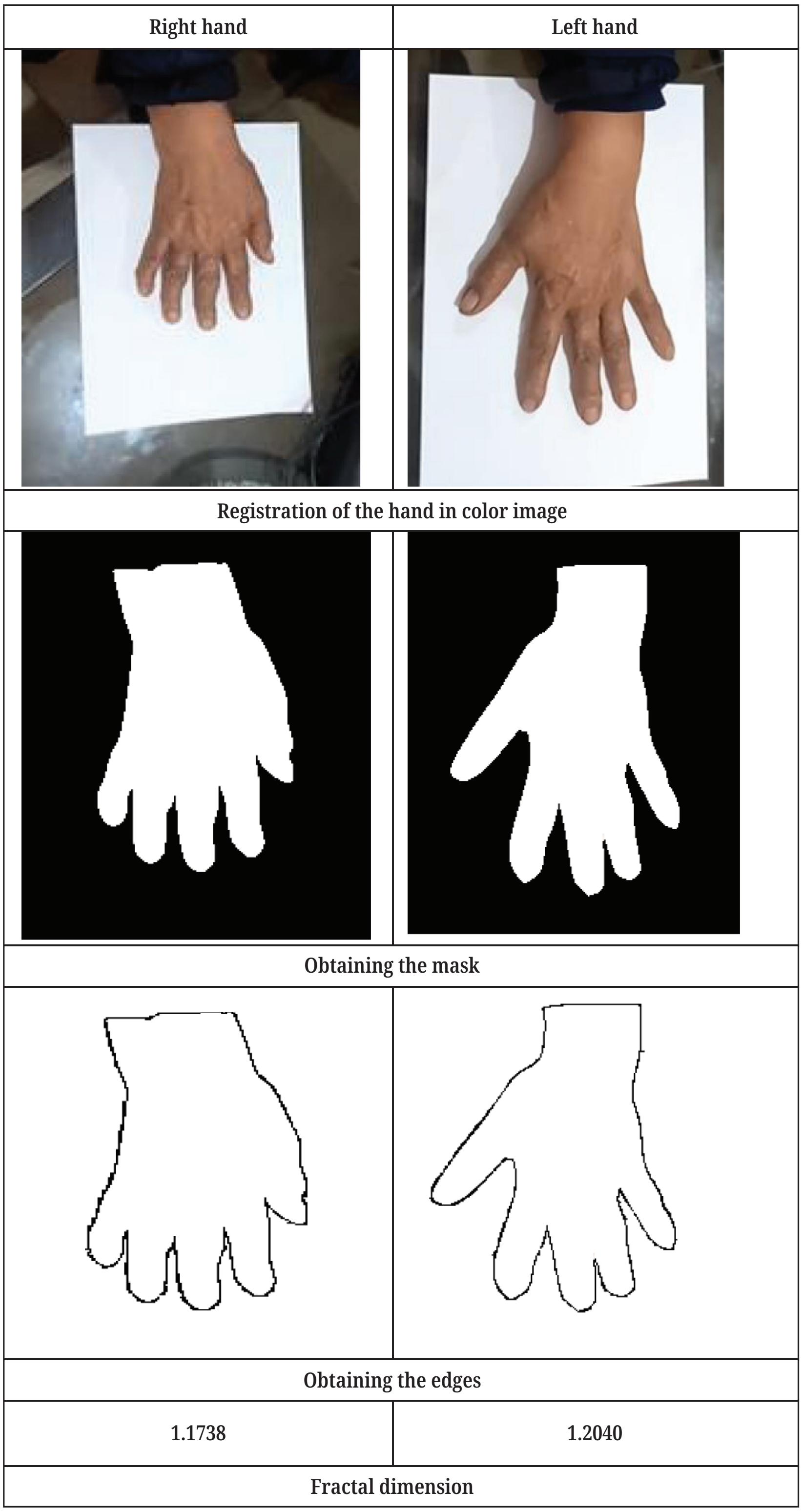


Fig. 6. Processes developed from image acquisition to fractal dimension computation

Figure 6 shows the use of the proposed methodology, from the recording of the images through the processing of the images and ending with the calculation of the FD. The calculation of the FD allows the analysis of the evolution of the degree of deformation of the fingers and hands.

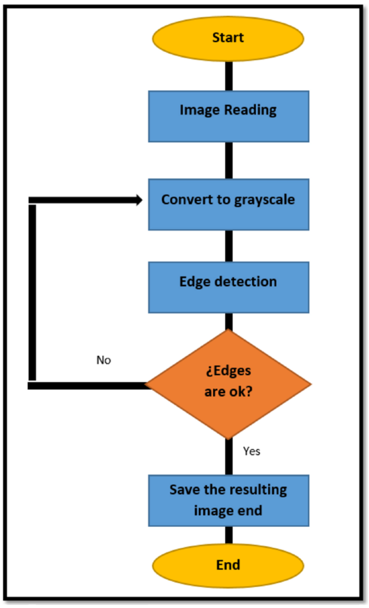


Fig. 7. Description of the image registration protocol

In Figure 7, the flow chart of the FD calculation process is presented, with emphasis on the processing of the images of the hands, until obtaining the final edges, which is the final image, and from where the FD is calculated. As long as the edges of the hands are not detected, the FD cannot be calculated, hence its importance in the proposed methodology.

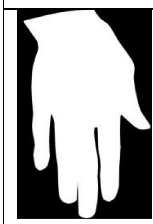
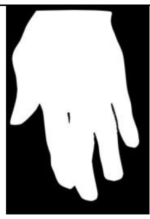
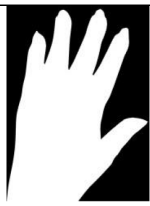
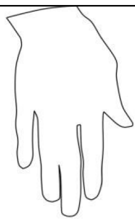
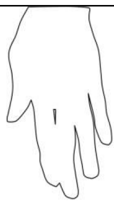
Image	Image	Image	Image
			
			
			
Fractal dimension	Fractal dimension	Fractal dimension	Fractal dimension
1.2631	1.2501	1.2412	1.2533

Fig. 8. Examples of application of the methodology

In Figure 8, you can see the application of the calculation of the FD for several images with the presence of arthritis. One of the characteristics is that each image has a particular shape; it is very difficult for a hand with arthritis to be the same with another, which allows us to identify that it has a different FD. The application where the technique of calculating the FD is exploited is for the control and monitoring of the shape of the hands, having more objective information on how the disease is evolving.

Table 1. Calculated values of the fractal dimension

Right Hand Fractal Dimension – Date 1	Right Hand Fractal Dimension – Date 2	Left Hand Fractal Dimension – Date 1	Left Hand Fractal Dimension – Date 2
1.2631	1.2501	1.2412	1.2533

Table 1 shows the data of the calculated values of the FD in the recording of both hands of a patient with arthritis. It can be observed that the recording was made at two different times. The proposed methodology allows us to analyze the variation of the fractal dimension.

We indicate that an object has the property of the FD, characterized by the shape of its contour. The property of the FD indicates that the value of the FD is constant, while the shape of the contour of the object does not vary. With this analysis, we can indicate that if in the recording of the shape of the fingers and hands, at different times they are equal, the fingers and hands have not undergone changes in their shape. This characteristic is very important in the analysis of the deformation of the fingers and hands, a product of arthritis, whose main manifestation is the deformation of the fingers in the area of the joints, which causes a change in the shape of the hands.

Analyzing the values in Table 1, we observe that the right hand has a first record of the FD of 1.2631 and a second record of 1.2501. This variation allows us to determine that there is a variation in the degree of deformation of the fingers and therefore of the hands. For the left hand, the first record is 1.2414 and the second record is 1.2533. In both cases, the patient's hands have presented a variation, which indicates that the arthritis disease is causing a change in the shape of the fingers and hands.

The proposed methodology, which is to analyze fingers and hands by processing images and calculating the FD, helps doctors in the process of analyzing and evaluating patients. In a first review, the patient cannot perceive the change due to the lack of information from previous records or due to the minimal perceived change. The proposed methodology allows for determining minimal changes in the shape of the fingers and hands, which would indicate that the disease is causing changes in the shape of the fingers and hands. The methodology helps in the evaluation processes to determine whether the medical indications are allowing the deformation of the fingers and hands to be controlled, as well as to analyze the evolution of the disease and the rate of deformation of the hands.

4 CONCLUSIONS

The conclusions we reached at the end of the study are related to explaining the implementation of the proposed methodology, starting with indicating that the proposed method is a way to objectively record the evolution of arthritis in the fingers, measured through the registration of the hands or feet, in our demonstrative case it was performed with the hands, this evolution of the arthritis is represented in morphological form through the malformation of the fingers and with them the change of the form and biophysics of the hand, leading to pain when trying to perform movements of the hands or feet.

From the process of registration of the images; it is recommended to perform the registration from the same distance in each of the records of the patients, in order to have a standard size and thus to have a real value in each of the calculations of the FD, with which we have a procedure for a temporal assessment of the state of progression of arthritis, measured through the advancement of the deformation of the hands or feet.

For image processing, it is recommended to use the best tool to handle the images, it can be from programs such as Paint and ImageJ, as well as from the development of applications using different programming languages, such as Python or Matlab. For the calculation of the FD, it can be done from any medium or application. For demonstration purposes, an algorithm based on the counting of boxes was implemented with the Matlab tool. In order to implement it, the pseudocode is indicated, and it is recommended to perform the processes or steps indicated to obtain the final image that corresponds to the edges of the hand or foot.

Finally, it is recommended to have the evidence of each of the evidences performed in order to be able to perform a visual analysis on the evolution of the arthritis and to be able to perform the evaluation through the variation of the FD. The methodology can be applied in other applications where it is required to evaluate, in a temporal, objective, and morphological way, the changes of an object that can be represented with an image.

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