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Chapter 4. SEGMENTATION AND THREE-DIMENSIONAL VISUALIZATION OF CHONDROMALACIA LESIONS OF THE FEMORAL HEAD

4.1. Introduction

The knee joint is the largest joint in the human body, in addition, it has a very complex structure and it is most vulnerable, immediately after the ankle joint, to the transmission of huge loads and forces in the human body. The structure is based on the articular surfaces of three bones: femur, tibia and knee cap. The joint is also reinforced with two crescent fibrous cartilage, called articular meniscus (*lat. menisci articulares*). It is further strengthened by external ligaments (collateral and joint bag) and cruciate ligaments (anterior and posterior). It is a hinged joint that allows bending and straightening movements, besides, with a bent joint, rotational movements are possible [3].

Articular cartilage occurs on the surface of the bone in all joints. It is mainly made up of protein molecules (collagen), proteoglycans, and water [4]. It is designed to carry heavyweight, thanks to the fact that it can change its shape under the influence of acting loads, which results in an even distribution of forces. When moving, it absorbs the friction between bones against each other, so that the joint can move smoothly [5].

Chondromalacia is a condition that occurs mainly within cartilaginous tissue. It can occur on the surface of the cap of all bones but is most often diagnosed within the knee joint. This is a condition that is characterized by softening, fraying of a large number of fibers on the surface of the articular cartilage, or in extreme cases its rupture. These pathological changes lead to its uneven thickness or local defect, causing the bones to rub against each other and, as a result, impair their proper movement. The reasons for

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this condition can be many, in addition to physiological changes in the structure or diseases such as rheumatoid inflammation of the joints or degenerative diseases, one can also mention biomechanical causes, which include: injuries, excessive use of the knee joint, flat feet, obesity.

The most commonly used non-invasive methods of imaging cartilage lesions include MRI (*Magnetic Resonance Imaging*) and Ultrasonography. Studies such as X-rays and CT (*Computer Tomography)* do not achieve sufficiently satisfactory cartilage visualization effects and are included in invasive studies due to the use of ionizing radiation. Exploratory arthroscopy stands out among the invasive imaging methods that provide the most information. Imaging diagnostics are aimed at showing the actual condition, the extent of pathological changes and precise visual information about cartilage, which can allow to plan treatment individually under the patient. Due to the need to classify the changes, according to their extent, depth, and reference of each of the tested cases to the existing guidelines, a four grades scale of Outerbridge chondromalacia was created (Table 4.1) [1]. In publication [2] the authors rely on the diagnosis of chondromalacia (and grade agency) based on MR images.

Table 4.1

Outerbridge grading of chondromalacia

Grade	Description
I	signal intensity alterations with an intact surface of the articular cartilage compared with the surrounding normal cartilage
II	partial thickness defect of the cartilage
III	fissuring of the cartilage to the level of the subchondral bone
IV	deep cartilage defects, exposed subchondral bone

4.2. Methodology

The procedure (Figure 4.1) begins with selecting the plane in which you want to segment. In the case of a front plane on the analyzed imaging series, the procedure slightly differs, this is due to the presence of imaging artifacts and the starting point must be selected depending on the cross-section up to three times, and then all images after segmentation are combined into one final one. After segmentation of the structure

in this plane, the procedure is already the same in all planes. When the image is loaded, a parameter is selected for the maximum intensity difference between pixels, which allows only pixels of the bone area to be segmented from the image, elements in the image with an intensity greater than or less than the set tolerance are not attached to the bone pixels. The starting point in the bone area is then selected, the intensity of which is the base value on which the procedure for integrating or not a pixel into the bone area is based. Attach pixels to the starting point using the region growing method. Once properly segmented, the next step is to save this structure as a .jpeg file so that it can be used to create a three-dimensional model from all images in a given plane. Based on this segmented structure, functionalities such as calculating the normalized surface area, finding a centroid, and calculating the dice factor value are also possible. In each plane, a photo vector was created from the .jpeg structures, which was the input for the function that creates the three-dimensional model.
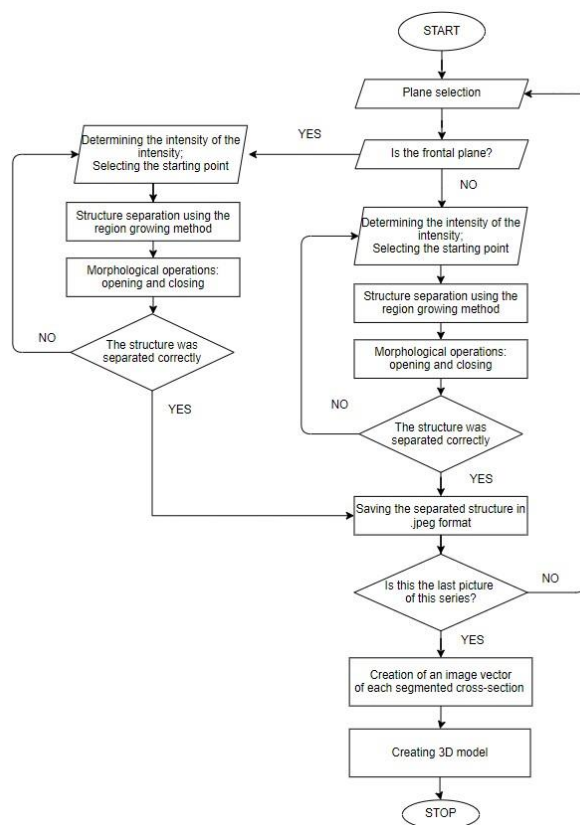

Fig. 4.1. Block diagram
Rys. 4.1. Schemat blokowy

Segmentation is the basic stage of image analysis that allows it to be divided into disjointed areas in terms of a given feature (e.g. Pixels Intensity). Through segmentation, it is possible to extract structures and analyze and interpret them later without

information redundancy. The segmentation method used in this work was the region growing method, which is based on the selection of the starting point and the value in mentioned earlier – the maximum difference in intensity. Then, in each iteration of the method, the analyzed pixel is analyzed by comparing its pixels in the neighborhood. Typically, it is a type of 4-neighborhood or 8-neighborhood. Both types are shown in Figure 4.2. The neighborhood type is nothing more than a topology of the position of the pixels surrounding the currently analyzed pixel in terms of intensity. If the inclusion criterion is met, the analyzed pixel is incorporated into the area with the starting point. Each pixel is subjected to this procedure. By combining all pixels, homogeneous areas are created in terms of the accepted criterion, which consequently leads to the segmentation of the selected structure [6].
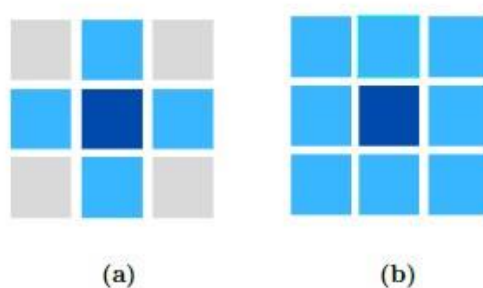

(a)   (b)

Fig. 4.2. Types of neighborhood: (a) 4-neighborhood, (b) 8-neighborhood
Rys. 4.2. Typy sąsiedztwa: (a) 4-sąsiedztwo, (b) 8-sąsiedztwo

For better results (Jagged Edge Alignments, Small Hole Fills), mathematical morphology operations are used, based mainly on dilatation and erosion operations on the currently analyzed pixel. The basic concept of mathematical morphology is the structural element. It is a set of pixels, most often in the form of a matrix of any shape, which in the case of binary images can take the value of 0 or 1. Examples of structural elements are shown in Figure 4.3. Each structural element has its own coordinate system, where the selected pixel is the reference point. This point is called a seed point. One of the two main operations is dilatation, which consists of the extension of the set of elements. In applying this operation, a structural element is applied to each pixel being analyzed, and if at least one of the pixels of the analyzed binary image is covered with a logical value of 1 in the structured element, the analyzed pixel is added to the resulting image. The image is characterized by the growth of the area. This operation is used when you need to smooth the edges, fill small holes, but it can also bring with it side effects such as assuming two small objects together. The operation in some way inverse to the one described above is erosion. Each pixel is also analyzed in this

operation, but the resulting value of 1 is determined only by that pixel when all pixels within the structural elements are non-zero. The final image after applying this operation is an image with some defects relative to the original image, with cavities dependent on the size of the structural element.
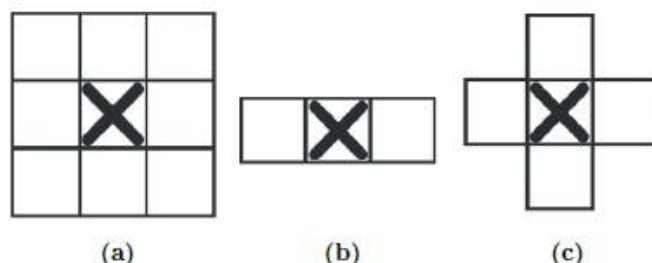

Fig. 4.3. Examples of structural elements
Rys. 4.3. Przykładowe elementy strukturalne

Combining these two operations after each other is called an opening or closing operation using the same structured element, depending on the order in which those operations are performed. If you perform an erosion operation and then a dilatation operation, we are talking about an opening that is designed to remove small details, small objects and separate two or more structures in the image from the analyzed image. Performing a dilatation and then erosion operation is called closing an image. This causes small holes to be filled in the image. The filling of these holes depends on the size of the structural element. Both operations are used to remove distortion from the image, so for better results, both of these operations can be performed sequentially after each other. The order in which the operation is performed does not significantly affect the final effect.

In order to assess the similarity of the segmented structure to the expert outline, the Dice coefficient was used. It is an indicator that allows you to determine spatial overlapping of two analyzed binary images. It is calculated according to equation 1. Values in the range <0;1> mean: 0 – total absence of similarity, no spatial overlap between the analyzed images. Value 1 – indicates the total overlap of images. Values between 0 and 1 indicate overlapping images to some extent, in part [7]. In segmentation, the expected value was expected to achieve results at DSC $\geq$ 0.8.

$$DSC = \frac{2(A \cap B)}{A+B}$$ (1)

4.3. Discussion and Results

4.3.1. Materials

Segmentation of the femoral head took place in images of the T1-weighted series of magnetic resonance imaging of the knee joint in the frontal plane and in images of the T2-weighted series of magnetic resonance imaging of the knee joint in the sagittal and transverse plane. The picture series in each plane counted:

- sagittal plane: 112 cross-sections, but only those on which bone structures were visible were used for segmentation, 72 cross-sections were used;
- frontal plane: 19 cross-sections, of which 18 were segmented femur;
- transverse: the series consisted of 18 cross-sections, each of which was segmented.

On each of the cross-sections is moved possible to segment an interesting structure. The Dice coefficient has been calculated to confirm the correctness of this segmentation. All results are presented in Figure 4.4 and Figure 4.5. The highest value of the coefficient has been achieved in the sagittal plane in cross-section 77 (Figure 4.6) and the smallest in the transverse plane in cross-section 4 (Figure 4.7). Green and magenta colors have been used for differences between superimposed structures and white for overlapping images. This value, in the case of the result with the highest value of coefficients, may be due to clear bone outlines, which in the image resulted in a large difference in intensity levels between pixels, which allowing for satisfactory results in the case of the area growth method. In cases coefficient value being lower, it may be watch that the segmented structure was larger than the expert stroke made. This could be due to a poor fit of the structural element for the mathematical morphology operation.
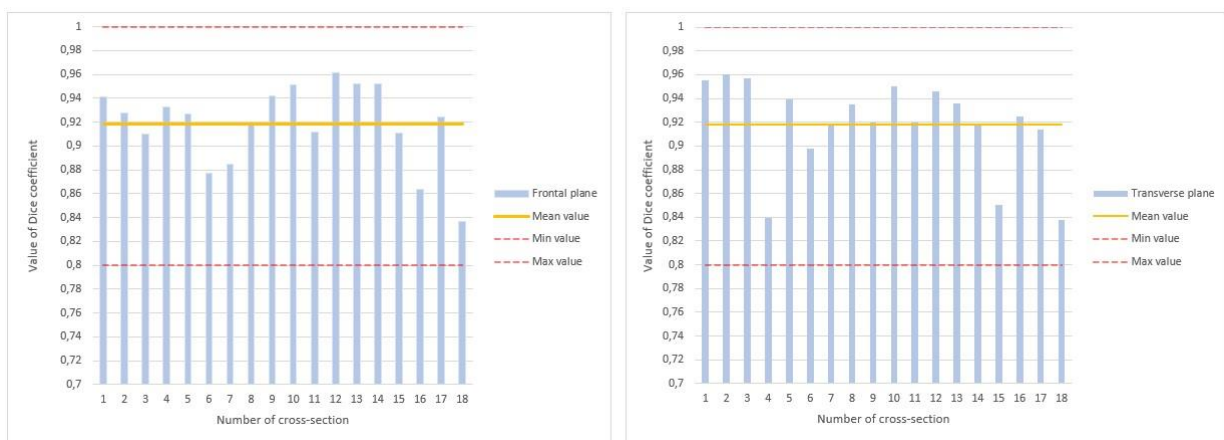
(a)   (b)

Fig. 4.4. Visualization of the results (a) in Frontal plane, (b) in Transverse plane
Rys. 4.4. Wizualizacja wyników (a) w płaszczyźnie czołowej, (b) w płaszczyźnie poprzecznej
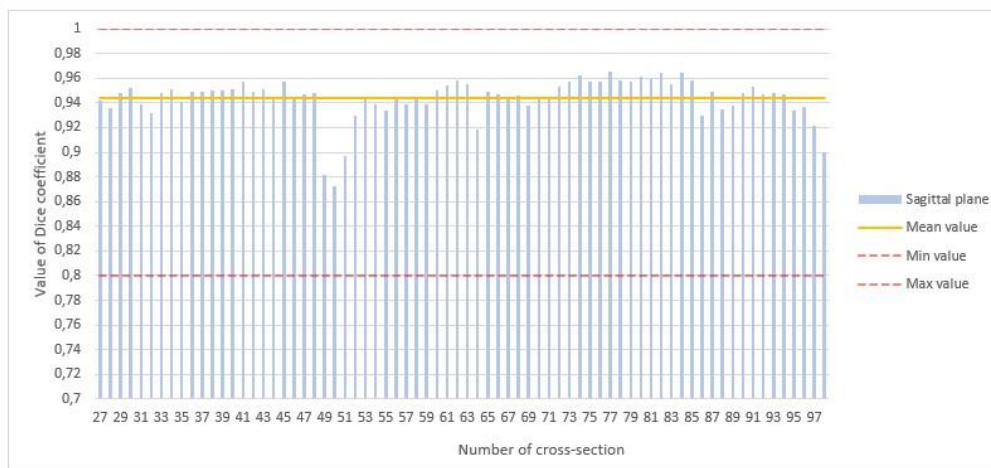
Fig. 4.5. Visualization of the results in Sagittal plane
Rys. 4.5. Wizualizacja wyników w płaszczyźnie strzałkowej
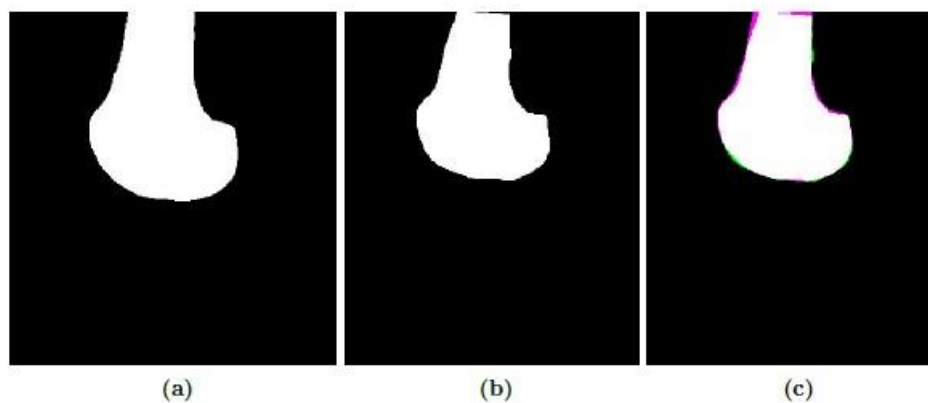

Fig. 4.6. Visualization of the highest coefficient value: (a) segmented structure, (b) expert outline, (c) overlay of both structures
Rys. 4.6. Wizualizacja największej wartości współczynnika: (a) wysegmentowana struktura, (b) obrys ekspercki, (c) nałożenie obu struktur
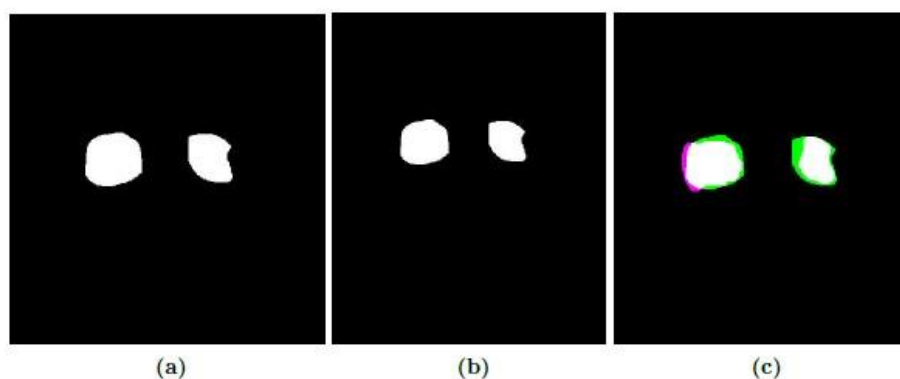

Fig. 4.7. Visualization of the smallest coefficient value: (a) segmented structure, (b) expert outline, (c) overlay of both structures
Rys. 4.7. Wizualizacja najmniejszej wartości współczynnika: (a) wysegmentowana struktura, (b) obrys ekspercki, (c) nałożenie obu struktur

For each plane, a three-dimensional model of the femoral head was created, which reflects the bone to a better or worse degree (Figure 4.8). The best model is the model in the sagittal plane, no doubt because it was in this plane that there were as many as 72 cross-sections, and the gap between them was small. Models in the transverse and frontal plane are created from fewer sections, which reduces their accuracy in model mapping. Additionally, the changes are best seen in the sagittal plane.
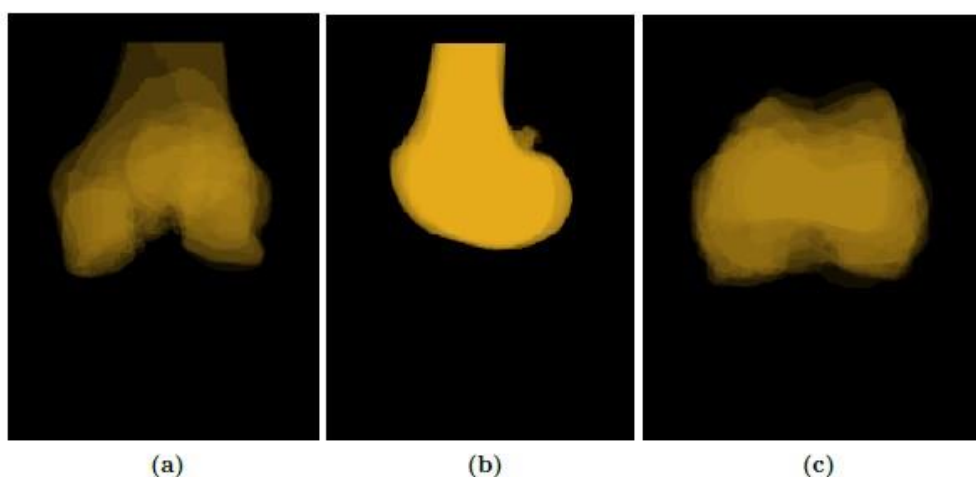

Fig. 4.8. Visualization in plane: (a) frontal, (b) sagittal, (c) transverse
Rys. 4.8. Wizualizacja w płaszczyźnie: (a) czołowej, (b) strzałkowej, (c) poprzecznej

With the increase in the degree of diagnosed chondromalacia, it becomes increasingly difficult to assess the extent of its pathological changes in magnetic resonance imaging. This model can provide doctors with information that can help them plan for further personalized treatment.

Bone segmentation with such changes is very demanding, mainly due to the size of the change and the slight differences in the intensity levels of the pixels that make up the femur. It is difficult to select the maximum intensity difference parameter because too little value causes the entire structure not to be segmented, while too much causes additional structures to be included in the bone area. In the imaging series for which segmentation has been performed, these changes are best seen in the sagittal plane in the T2-weighted MR series.

Segmentation based on thresholding methods is the oldest and fastest, but the disadvantage of this group of methods is low accuracy compared to other methods [8]. In the discussed article, the authors recommend the method of active contours as a better method of segmentation based on the obtained results, which give much better results. Other methods that give good segmentation results recommended by the authors are

graph-based segmentation, atlas-based method, model-based image segmentation and Machine Learning based methods.

In the future, the development plan is to try this method on changes in chondromalacia on other imaging studies that include other degrees of the Outerbridge scale.

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Abstract

The purpose of this paper is to present the results of the segmentation of the femoral head with changes in chondromalacia in the base of the medial bone load zone of the second degree of the femur from MR images. The article shows the manual segmentation method based on the region growing method and the steps involved in applying mathematical morphology to improve the segmented structure. Segmentation was performed in pictures in three planes: transverse, sagittal and frontal. From the segmented sections, a three-dimensional models were created to illustrate the appearance of the bones. All steps have been implemented in the MATLAB environment using the Image Processing toolbox. To confirm the correctness of the segmentation, a Dice coefficient was used, the values of which were in the range of 0.839 to 0.965.

Keywords: chondromalacia, segmentation, 3D vizualization, computer aided treatment.