Analysis of experimentally measured samples of contact stress distribution in the hip joint prosthesis.

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Abstract:
The human hip joint is a spherical joint where the spherical bone surfaces of femur and acetabulum, which are covered by cartilage, are in close contact. It has been suggested recently, that the acetabular fossa contributes to a more uniform articular contact stress distribution and a consequent decrease in the peak contact stress. The goal of this work is to prove this assumption experimentally by analysing the distribution of the contact stress in the spherical hip joint prosthesis. The distribution of the stress of spherical hip joint was measured with FUJI prescale film using testing system MTS 858.2 Mini Bionix in accordance with ISO 14242-1 standard. Measured film samples were analyzed by custom-made computer program. Results show nonuniform stress distribution with high sensitivity to 'crinkle artefacts'*. Result are in good agreement with mathematical model.*

Key words:
hip joint, contact stress, FUJI prescale film, crinkle artefact.

1. Introduction

The hip joint is a spherical joint, which is whole covered by cartilage. The cartilage covers almost all the femoral head whereas the central and inferior part of the acetabulum[1].The acetabular articular cartilage attains a charakteristic horseshoe shape called the facies lunata - the curved articular surface that surrounds the acetabular fossa and articulates with the head of the femur.

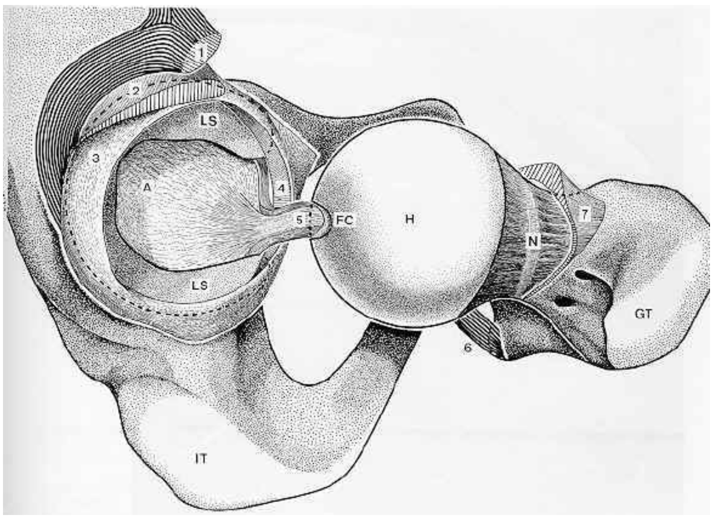

Fig. 1 *The human hip join – (A) acetabular fossa, (LS) facies lunata, (H) a head of femur*

The shape of the cartilage thus influences the mechanical conditions in the hip. In the study Acetabular cartilage and hip joint contact stress distribution, written by M. Daniel et al. 2005,

was intended to estimate how the contact stress distribution in the human hip joint is influenced by the characteristic horshoe shape of the acetabular cartilage.[3]
In this work is experimentally verified distribution of the contact stress in the spherical hip joint implant.

2. Forces in the hip joint.

To estimate the contact stress distribution in the hip joint, the resultant force transmitted between the femoral head and acetabulum ($R=(R_x, R_y, R_z)$) should be known. To assess the value of R, a biomechanical model of the human hip joint was used in order to solve equilibirum equations for moments and forces acting on the pelvis in a one-legged stance.[5]

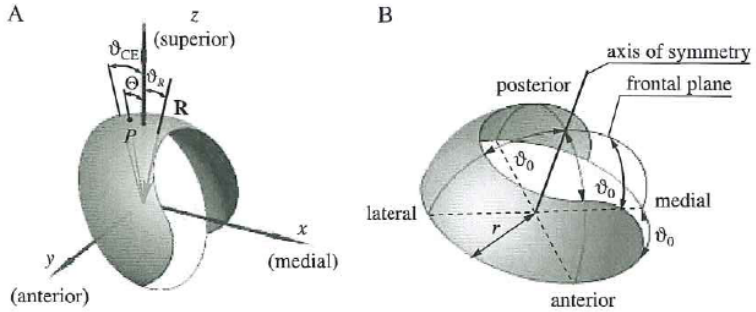

Fig. 2 *Schematic presentation of the coordinate system (A) and geometrical model of the articular cartilage (B)[3]*

On fig. 2A is coordinate system in the human hip joint. The origin of the system was chosen in the centre of the acetabular shell so that *x* and *z* axes lie in the frontal plane and the *y* and *z* axes in the sagittal plane of the body. In the one-legged stance, the hip joint resultant force R lies almost in the frontal plane of the body [3] The force R can be expressed as:

$$R=(R.\sin\upsilon_R, 0, R.\cos\upsilon_R) \tag{1}$$

here υ_R inclination of R with respect to the saggital plane. It was found that for a human with reference geometry of the hip and a body weight of 800N: R = 2160N and $\upsilon_R=5°$ [5]

The contact stress integrated over the articular surface $\int_A pdA$ should be equal to the force transmitted through the hip joint R:

$$(\int_A pdA)_x = R_x, \qquad (\int_A pdA)_y = R_y, \qquad (\int_A pdA)_z = R_z. \tag{2}$$

Where *A* is the area of non-zero contact stress. Equations (2) represent a system of three integral equations for three unknown quantities.

To understand better the basic mechanism of the stress distribution. See fig. 3

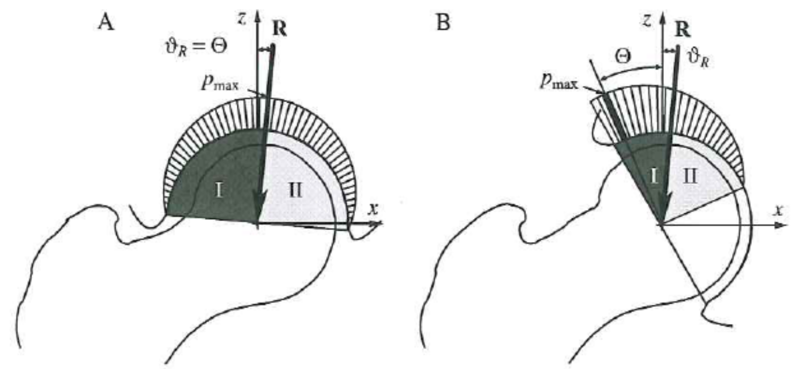

Fig. 3 *Schematic figure of the stress distribution acting on the articular surface for two different position of acetabulm.*

On the Fig. 3 is shown distribution of the contact stress. If the hemispherical contact articular surface is symmetric with respect to the force *R(A),* the stress pole coincides with the direction of the resultant force *R*. If the acetabulum is rotated in medial direction *(B),* the stress distribution is asymmetric with respect to the direction of the resultant force *(R)* and the stress pole is moved to region I.[3]

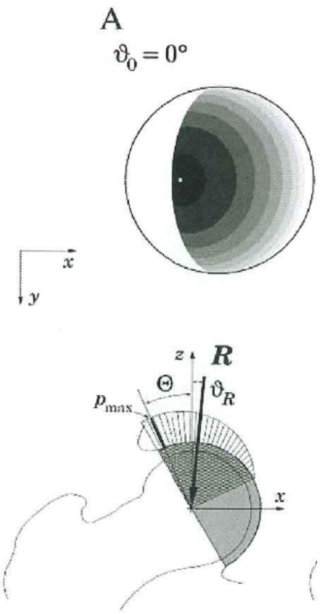

Fig. 4 *Upper figure is projected on the transversal plane and lower figure on the frontal plane.*

The upper figure *(4)* is mathematical modell of contact stress distribution.

3. How was measured distribution of the contact stress?

3.1 FUJI prescale film

Distribution of the contact stress was measured with FUJI prescale film. Fuji *Prescale*™ film is used to measure contact pressures. The pressure sensitive film structure consists of micro-encapsulated color forming and developing material. When pressure is applied to the film, a red color impression is formed in varying density according to the amount of pressure and pressure distribution. Simply place Fuji *Prescale* film between any two surfaces which come into contact. Varying colors of red patches will instantly appear revealing the pressure distribution between the surfaces. The intensity of the red colors of the Fuji *Prescale* film is related to the amount of pressure applied to it, the more intense the color, the greater the pressure. There are six different film types available ranging from 0.2 to 300 MPa (28 to 43,500 PSI) [6]

Fig. 5 *Hip joint prothesis with FUJI prescale sample after loading.*

3.2 Testing system Mini Bionix

The laboratory in Dejvice is equipped with the peak testing system MTS 858.2 Mini Bionix that is unique for ability to apply an axial force and a torque simultaneously. The testing system has an axial load range of 0 to 25 kN. The torque is in the range 0 to 100 Nm. This system was modernized and upgraded in the year 2006. Now the system is equipped with unique simulator enabling the loading with 8 degrees of freedom (3 displacements and 5 rotations). This simulator is rare in all of Europe. For its construction, it is primarily intended for the exacting spine testing. Through the adjustment of configuration, this simulator is possible to use for other experiments.[7]

Fig. 6 *MiniBionix testing system with hip joint prothesis in the holder.*

3.3 Experiment

Hip joint prothesis was fixed in the holder of corrosion – resistant material (construction and dimensions to suit test specimen and testing machine) medium in the holder is PMMA – plexiglas. Fixator and conditions were in accordance with ISO 7206. For statical loading.

It was measured - **Set A**: 7 MS FUJI prescale film samples (5mm x 100mm), loading force 200N, 400N, 800N, 1200N, 1600N, 2000N, 2400N.

Set B: 5 MS FUJI prescale film samples (5mm x 100mm), loading force 2000N (verification) + 1 sample (10mm x 100mm), loading force 2000N.

FUJI samples were placed on the femoral head and fixed with sticky tape *(Fig. 5)* than started loading process. Results were analyzed by custom – made computer program.

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Fig. 6 *Sample no.6. Loading force 2000N*

4. Analysis of experimentally measured FUJI film samples.

4.1 Custom – made program

The program was created in MatLab. First part of the program analyzes color of the color table from FUJI and save as RGB table.

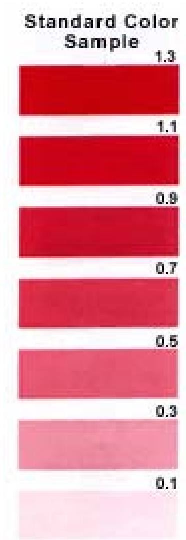


Fig. 7 *Color table from FUJI.*

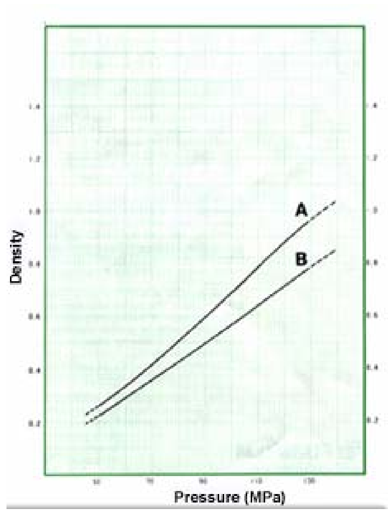


Fig. 8 *Relation between intensity of red colour and pressure*

```
imrgb = imread(‚color_table.tif‘) %
[im_height,im_width,pocetbarev] = size(imrgb); %zjisteni velikosti
obrazku
r=imrgb(:,:,1);  % ulozeni jednotlivych barevnych slozek
g=imrgb(:,:,2); % ulozeni jednotlivych barevnych slozek
b=imrgb(:,:,3); % ulozeni jednotlivych barevnych slozek
prumerne_r(1) = round(mean(mean(r))); %vypocteni prumerne hodnoty
z jeednotlivych barev
prumerne_g(1) = round(mean(mean(g))); %vypocteni prumerne hodnoty
z jeednotlivych barev
prumerne_b(1) = round(mean(mean(b))); %vypocteni prumerne hodnoty
z jeednotlivych barev


polynom_r = polyfit([0.3 0.5 0.7 0.9 1.1 1.3 1.5],prumerne_r,2);
%prolozeni polynomem druheho radu
polynom_g = polyfit([0.3 0.5 0.7 0.9 1.1 1.3 1.5],prumerne_g,2);
%prolozeni polynomem druheho radu
polynom_b = polyfit([0.3 0.5 0.7 0.9 1.1 1.3 1.5],prumerne_b,2);
%prolozeni polynomem druheho radu
```

Compare color to pressure.

```
r_ref=round(polynom_r(1).*x.^2+polynom_r(2).*x+polynom_r(3));
g_ref=round(polynom_g(1).*x.^2+polynom_g(2).*x+polynom_g(3));
b_ref=round(polynom_b(1).*x.^2+polynom_b(2).*x+polynom_b(3));
```

Choose the sample for the analysis.

```
imrgb = imread(UIGETFILE('*.*','Choose the picture for the analysis
...'));
[im_height,im_width,pocetbarev] = size(imrgb);
imrgb =
imrgb(1:(fix(im_height/grid_vzorku))*grid_vzorku,1:(fix(im_width/grid_vz
orku))*grid_vzorku,:);
[im_height,im_width,pocetbarev] = size(imrgb);
r_vzorek=imrgb(:,:,1);
g_vzorek=imrgb(:,:,2);
b_vzorek=imrgb(:,:,3);
```

Analysis.

```
for i=1:(im_height/grid_vzorku)
    for j=1:(im_width/grid_vzorku)

        r_vzorek_prum(i,j)= round(mean(mean(r_vzorek((i-
1)*grid_vzorku+1:i*grid_vzorku,(j-1)*grid_vzorku+1:j*grid_vzorku))));
        g_vzorek_prum(i,j)= round(mean(mean(g_vzorek((i-
1)*grid_vzorku+1:i*grid_vzorku,(j-1)*grid_vzorku+1:j*grid_vzorku))));
        b_vzorek_prum(i,j)= round(mean(mean(b_vzorek((i-
1)*grid_vzorku+1:i*grid_vzorku,(j-1)*grid_vzorku+1:j*grid_vzorku))));

       %hledání odpovídajícího tlaku k danému výřezu
       [nic velikost_x]=size(x);
       for cykl=1:velikost_x
            r_odchylka(cykl)=abs(r_ref(cykl)-r_vzorek_prum(i,j));
            g_odchylka(cykl)=abs(g_ref(cykl)-g_vzorek_prum(i,j));
            b_odchylka(cykl)=abs(b_ref(cykl)-b_vzorek_prum(i,j));
```

```
soucet_odchylka(cykl)=r_odchylka(cykl)+g_odchylka(cykl)+b_odchylka(cykl)
;
       end
       [minimum pozice]=min(soucet_odchylka);
       vysledna_mapa_tlaku(i,j)=x(pozice); %vysledna mapa tlaku pro
paletu 0,3 - 1,5

    end
end
```

Compare pressure [Pa] to pressure [color]

```
polynom_prevodni_tabulky_A = polyfit([0.3 0.5 0.7 0.9 1.1 1.3 1.5],[12
18 25 30 35 41 49],2);
polynom_prevodni_tabulky_B = polyfit([0.3 0.5 0.7 0.9 1.1 1.3 1.5],[14
22 28 35 43 54 70],2);

prevodni_tabulka(1,:)=x;
prevodni_tabulka(2,:)=round(polynom_prevodni_tabulky_A(1).*x.^2+polynom_
prevodni_tabulky_A(2).*x+polynom_prevodni_tabulky_A(3));
prevodni_tabulka(3,:)=round(polynom_prevodni_tabulky_B(1).*x.^2+polynom_
prevodni_tabulky_B(2).*x+polynom_prevodni_tabulky_B(3));

[velikost_mapy_x velikost_mapy_y] = size(vysledna_mapa_tlaku);
for i=1:velikost_mapy_x
    for j=1:velikost_mapy_y
        for cykl=1:velikost_x
           if vysledna_mapa_tlaku(i,j)==prevodni_tabulka(1,cykl)

vysledna_mapa_tlaku_v_pascalech(i,j)=prevodni_tabulka(2,cykl);
           end
        end
    end
 end
```

Printing figures.

```
figure(1)
 mesh(vysledna_mapa_tlaku_v_pascalech)
title('The distribution of the contact stress in the hip joint
prothesis');
xlabel('width [Pixels]');
ylabel('height [Pixels]');
zlabel('pressure [MPa]');
colorbar

figure(2)
 contour(vysledna_mapa_tlaku_v_pascalech)
title('The distribution of the contact stress in the hip joint
prothesis');
xlabel('width [Pixels]');
ylabel('height [Pixels]');
colorbar
```

5. Results

Sample 1 - *The loading force 400N.*

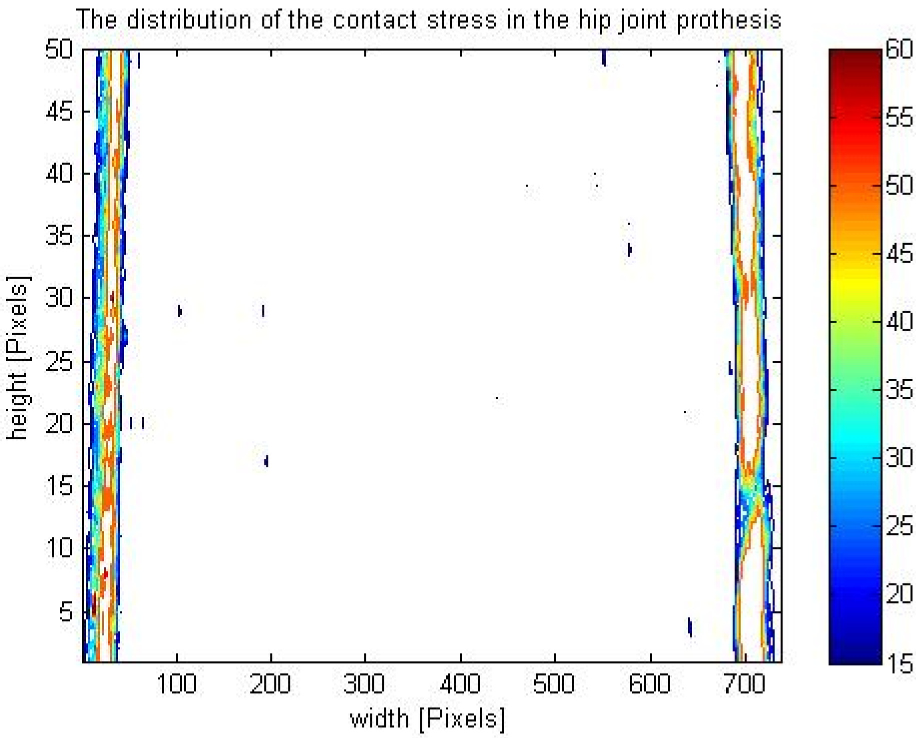


Figure 9 - *The conture of the sample 1, the resolution is 50x736 pixels. The loading force 400N.*

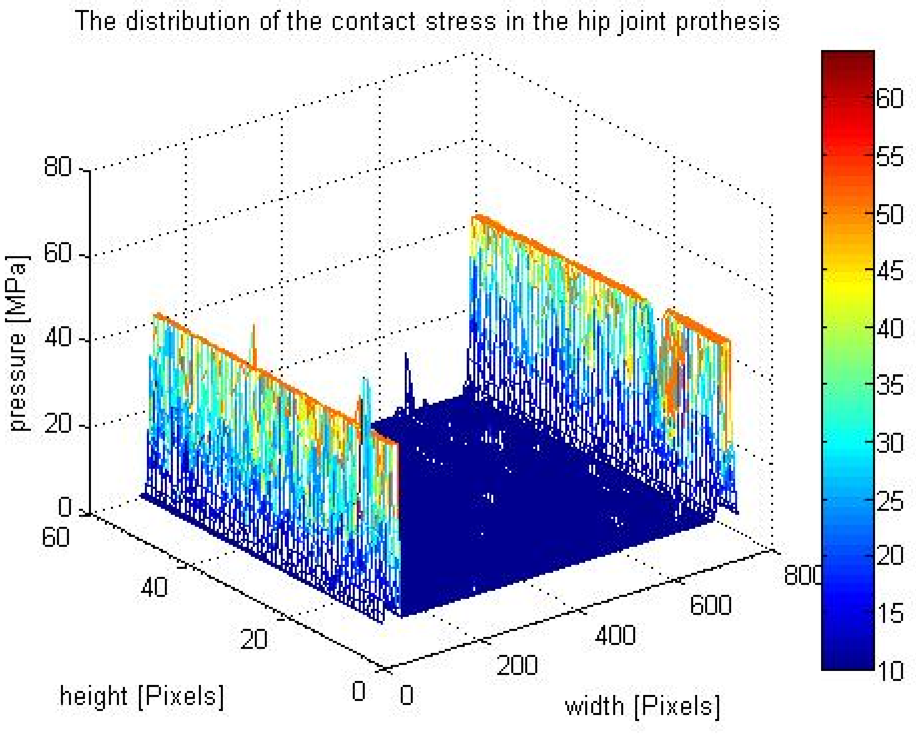


Figure 10 - *The 3D figure of the distribution of the contact stress in the hip joint prothesis. The loading force 400N.*

Sample No. 2:

M  L

Sample 2 - *The loading force 800N.*

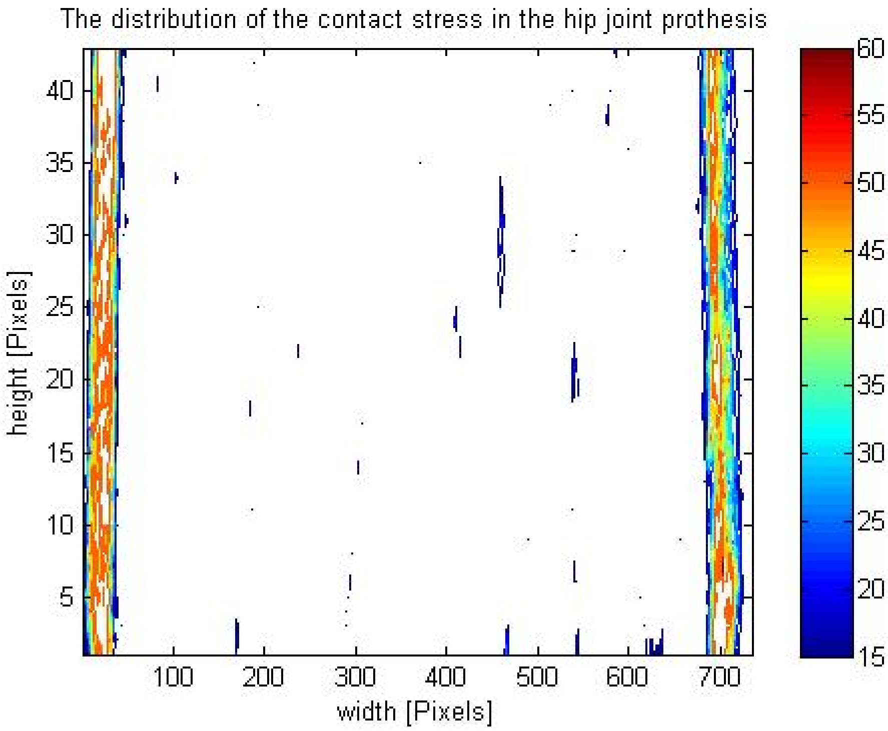


Figure 11 - *The conture of the sample 2, resolution 50x736 pixels. The loading force 800N.*

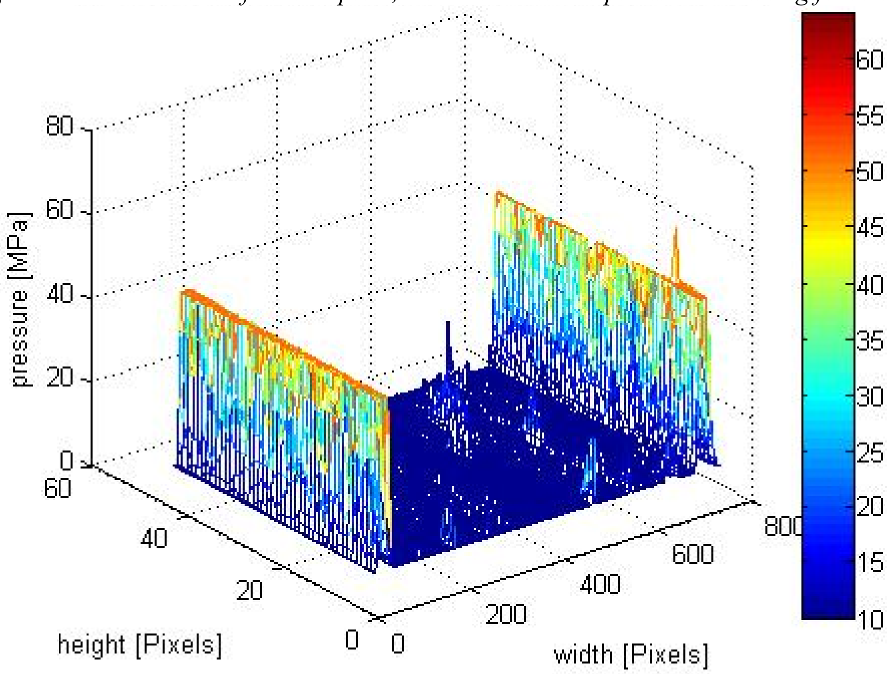


Figure 12 - *3D figure of the distribution of the contact stress in the hip joint prothesis. The loading force 800N.*

Sample No. 3:

Sample 3 - The loading force 1200N.

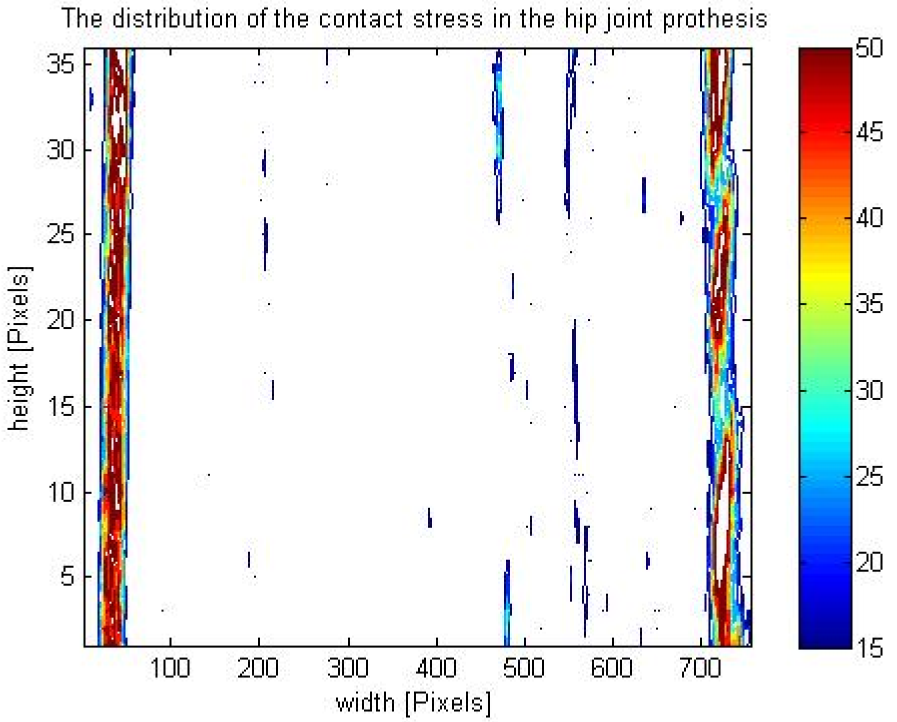


Figure 13 - *The conture of the sample 3, resolution 50x736 pixels. The loading force 1200N.*

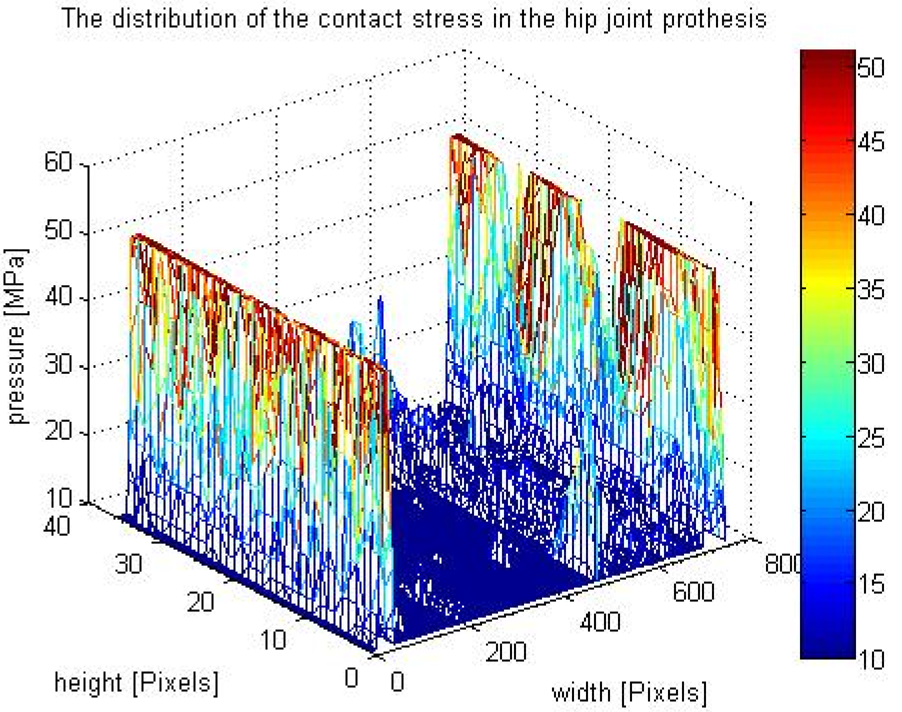
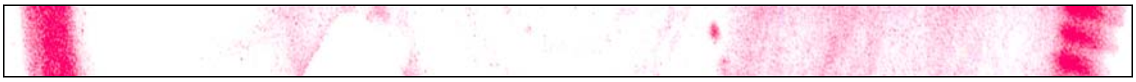


Figure 14 - *3D figure of the distribution of the contact stress in the hip joint prothesis. The loading force 1200N.*

Sample No. 4:

M  L

Sample 4 - *The loading force 1600N.*

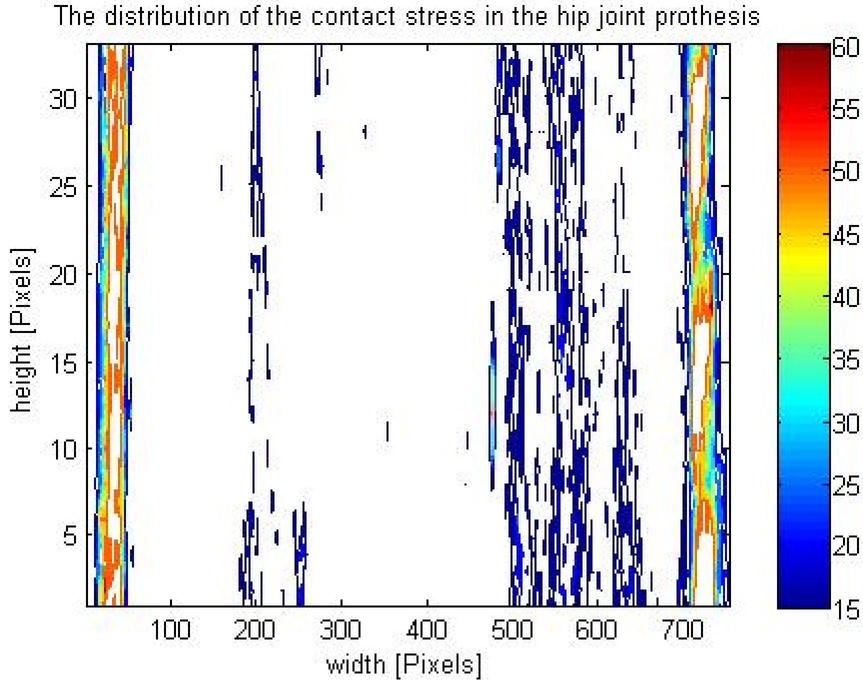


Figure 15 - *The conture of the sample 4, resolution 50x736 pixels. The loading force 1600N.*

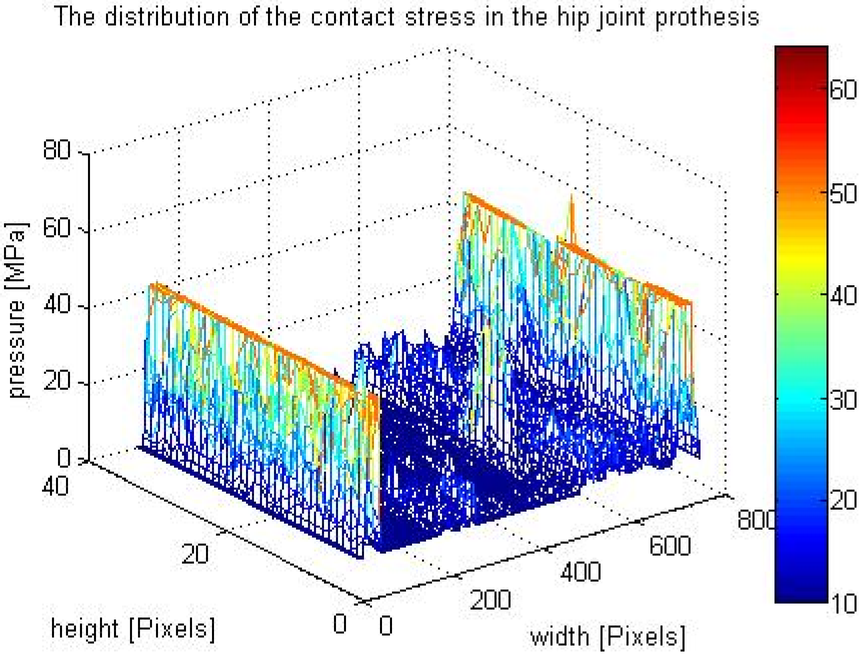


Figure 16 - 3D figure of the distribution of the contact stress in the hip joint prothesis. The loading force 1600N.

Sample No. 5:

M  L

Sample 5 - *The loading force 2000N.*

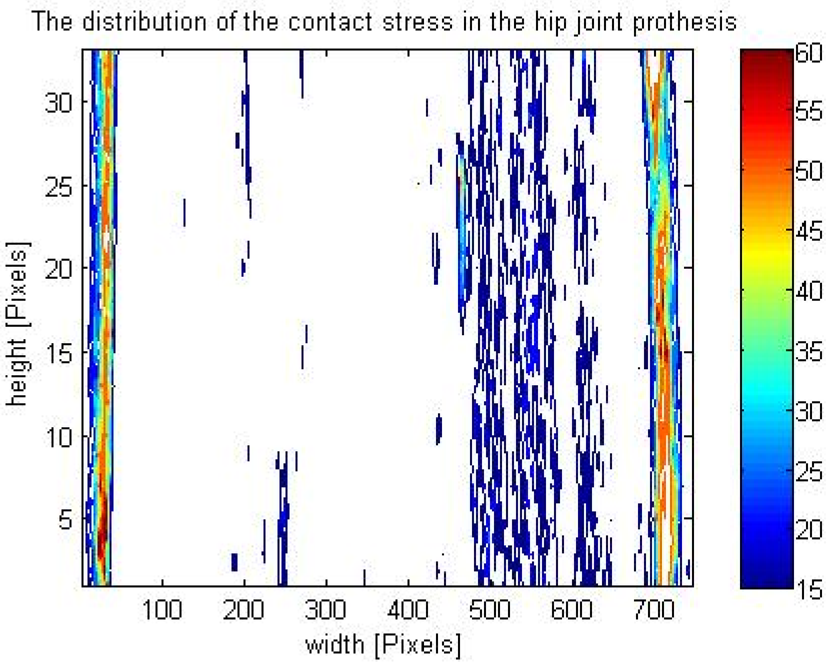


Figure 17 - *The conture of the sample 5, resolution 50x736 pixels. The loading force 2000N.*

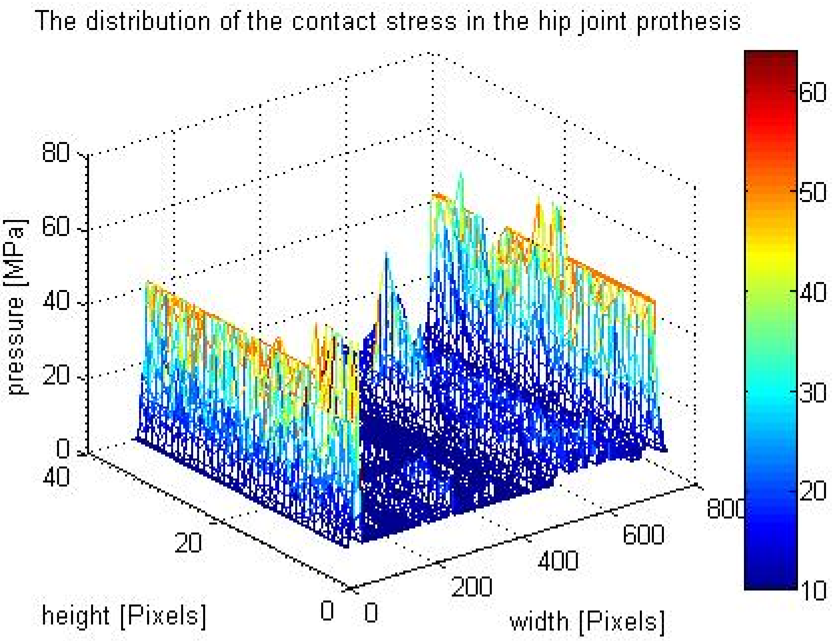


Figure 1 - *The 3D figure of the distribution of the contact stress in the hip joint prothesis. The loading force 2000N.*

Sample No. 6:

M 

Sample 6 - *The loading force 2400N.*

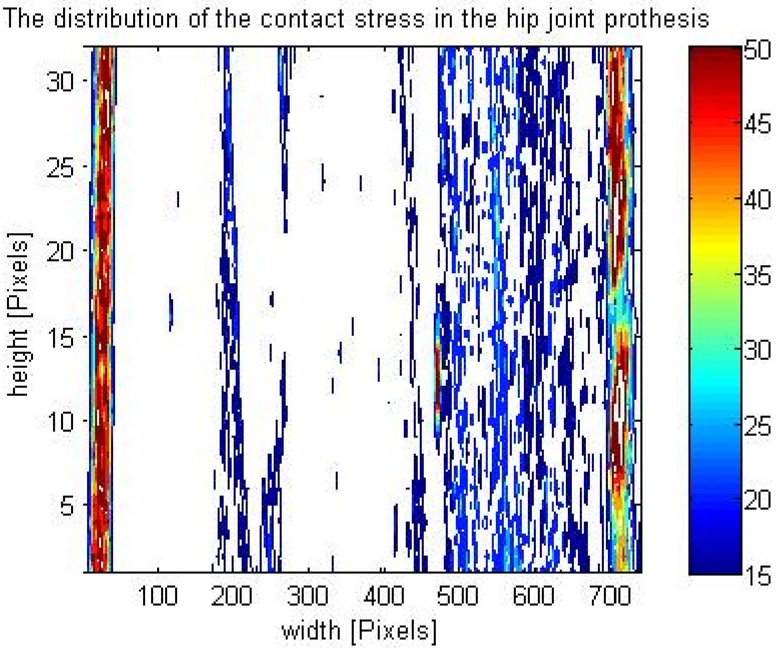


Figure 19 - *The conture of the sample 6, resolution 50x736 pixels. The loading force 2400N.*

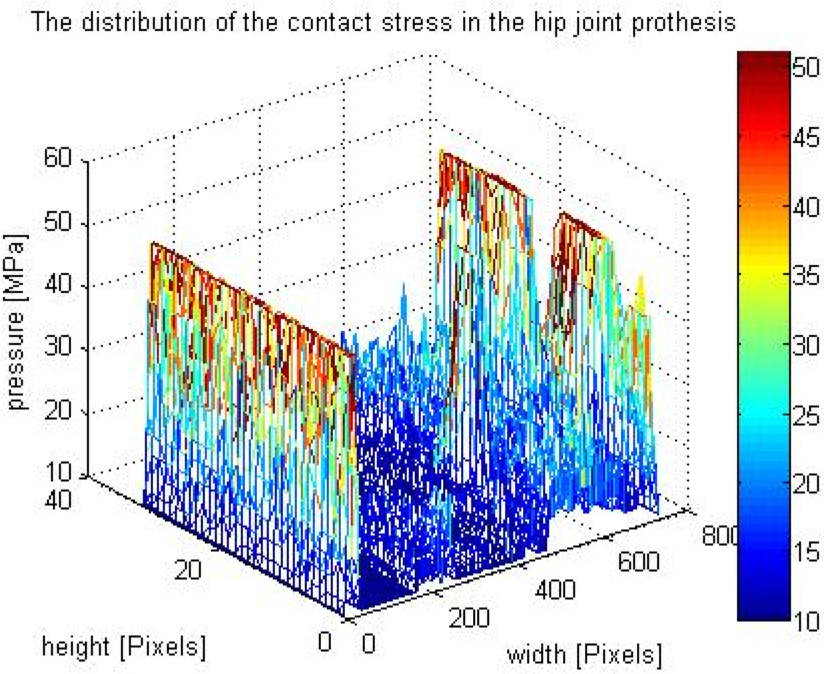


Figure 20 - *3D figure of the distribution of the contact stress in the hip joint prothesis. The loading force 2400N.*

6. Conclusion

The custom – made computer program is universal and is able to operate with high accuracy. But in this case is not important to have high accuracy because measured samples were scanned to computer and the color of these samples was influenced by the scanner. Results show nonuniform stress distribution with high sensitivity to 'crinkle *artefacts*'. Results are in good agreement with mathematical model.

List of symbols:

R	Resultant force [N]
p	Pressure [MPa]
A	Area
MS	Medium Pressure *prescale* film [10 – 50 MPa]

Applied literature:

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[3] Daniel et al , *The shape of acetabular cartilage optimizes hip contact stress distribution*, M. 2005, J. Anat. 207, p. 85 – 91

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