BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LXIII No. 1/2011	107 - 116	Seria Tehnică

Experimental Study on the Behaviour of Osteochondral Cylinders Transplanted at the Femural Condyle in the Case of an Autologous Osteochondral Transplant

Adrian Pascu[*], Valentin Oleksik[*], Radu Fleacă[**], Mihai Roman[**], Cristian Deac[*], Mihaela Oleksik[*]

[*] "Lucian Blaga" University of Sibiu, "Hermann Oberth" Faculty of Engineering, Emil Cioran Street no. 4, Sibiu, 550025, Romania
e-mail: adrian.pascu@ulbsibiu.ro, valentin.oleksik@ulbsibiu.ro, cristian.deac@ulbsibiu.ro, mihaela.oleksik@ulbsibiu.ro

[**] "Lucian Blaga" University of Sibiu, "Victor Papilian" Faculty of Medicine, Pompeiu Onofreiu Street no. 2-4, Sibiu, 550166, Romania
e-mail: radu.fleaca@doit.ro, mroman1969@yahoo.com

Abstract

This paper, presents the experimental analysis on a bovine knee having an osteochondral autologous transplant at the level of a femural condyle seeks to assess the transplanted cylinders' behaviour under pressure. Experimental determinations were realised for various cylinder diameters and for various surfaces of the chondral lesion. There was used a testing installation realised by the authors and the strains measurement system Aramis. The aim is to determine whether the mechanical stress applied to the transplanted cylinders determines their displacement and the subsequent annullment of the biological and functional result of the transplant.

Key words: *plugs, osteochondral autologous transplantation, Aramis device, strain*

Material and devices used

The speciality literature accepts as indication for the osteochondral autologous transplant a chondral lesion at the level of the femural chondyle with an area of 2 – 4 mm^2. Although there othert studies regarding the pressures developed at the level of the chondral defect and their analysis, currently there exist only few studies on the computerised analysis of the behaviour of transplanted chondral cylinders function of the size and shape of the chondral defect. For these reasons too, this paper aims to realise an experimental analysis of the compression behaviour of the osteochondral cylinders transplanted on the femural condyle of a bovine femur, considering that the transmission of forces occurs also by means of the tibia.

For this, there were run compression tests on a tensile, compression and buckling testing machine Instron 5587, in order to determine the manner of deformation occuring in the femural condyles, at forces varying from 0 N to levels that lead to the sinking of the transplant along the femur's axis. In order to determine the strains and stresses in the transplant area, there was used both the software available on the Instron machine and an optical method that uses an optical equipment Aramis 2M.

On the femural condyles of the bovine femurs used for this purpose, there were created chondral defects with areas of 2.5 cm^2 and 4 cm^2 of different standardised shapes (Figure 1), and then the osteochondral transplant was realised at the chondral defects, using cylinders with a diameter of 6 mm and 8 mm. Figure 2 presents some of the osteochondral cylinders used for the transplant (D_{cyl} = 8 mm, L_{cyl} = 20 mm).

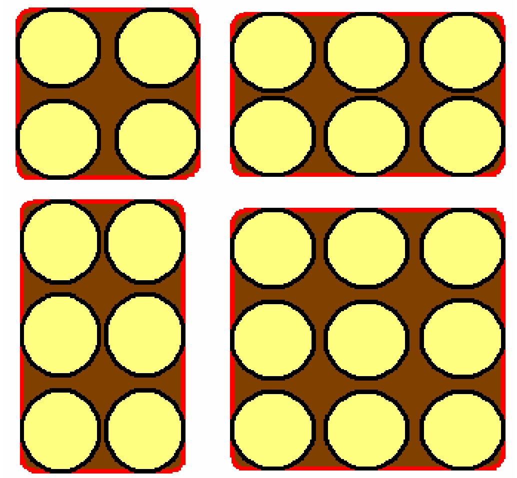


Fig. 1 Sketches for realising the chondral defects and the positioning of osteochondral cylinders

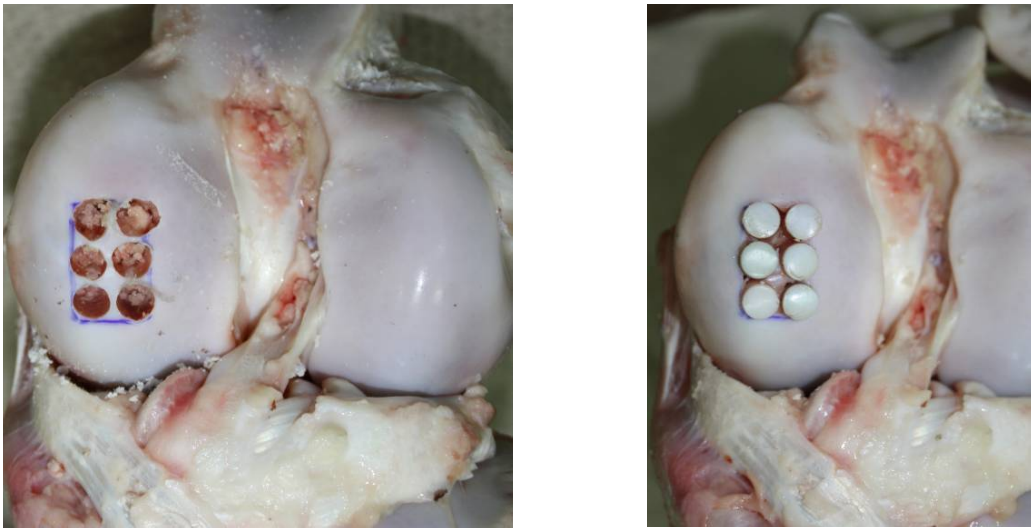
Fig. 2 Osteochondral cylinders used for the transplant

The dimensions of the femural condyles and the thickness of the articular cartilage at the chondral defect are presented in table 1. The condyles' dimensions were measured at their maximal level using a calliper. The thickness of the articular cartilage at the chondral defect was measured directly after realising the defect, measuring the thickness of the tissue on the extracted osteochondral cylinders. From the obtained data it can be seen that the lot is homogeneous with regard to the anatomical dimensions of the condyles and to the cartilage thickness in the defect area. The distribution of the knees on experimental groups was at random.

Table 1. Anatomic characteristics of the employed bovine femural condyles

Curr. no.	Side	Condyle thickness [mm]		Condyle height [mm]		Cartilage thickness [mm]
		CI	CE	CI	CE	
1.	L	55.18	55.32	79.48	74.87	0.79
2.	L	54.13	52.09	73.20	74.37	0.84
3.	R	55.78	49.67	75.68	72.83	1.06
4.	L	56.73	55.91	80.12	75.46	1.00
5.	R	52.21	50.37	74.83	74.82	1.20
6.	R	49.87	52.15	73.66	76.55	0.88
7.	R	51.46	49.04	72.93	72.18	0.99
8.	L	56.39	54.92	75.42	73.87	0.96
9.	R	53.94	53.55	77.83	75.76	1.12
10.	L	54.83	52.73	75.93	76.53	1.06
11.	R	51.47	50.22	74.77	73.66	0.96
12.	R	55.32	50.72	75.93	76.45	1.01
13.	L	55.93	53.79	78.77	73.52	0.74
14.	R	53.95	50.82	73.57	74.38	0.86
15.	R	52.72	56.72	76.55	71.62	1.06
16.	L	53.94	52.83	74.33	75.82	1.10
Average		**53.85**	**52.68**	**76.07**	**74.52**	**0.97**

Figure 3a presents the aspect of the condyle after preparing the area for realising the osteochondral transplant, with the receiving tunnels, while in figure 3b there is presented the final aspect, after carrying out the transplant on the femural condyle (both for D_{cyl} = 8 mm, S = 4 cm^2).



(a) Osteochondral defect - receiving tunnels **(b)** Covered osteochondral defect

Fig. 3 Osteochondral defect (D_{cyl} = 8 mm, A = 4 cm^2), aspect before and after carrying out the osteochondral transplant at the realised defect

Similarly, there were realised osteochondral defects and transplants for cylinders with a diameter of 6 mm.

Realising the tests and acquisition of the experimental data

After realising the defect, the osteochondral transplant was realised according to the planning, with cylinders taken from the femural trochlea of the same femur. After that, each femur was prepared for the optical acquisition of data using the Aramis 2M system, by covering the femur's surface with a white matte adherent, quick-drying paint, after which a graphite spray was pulverised on the areas exposed to the image capturing system.

In a next stage, the knee was placed in extension on the experimental installation by repositioning the fastening screws in the corresponding holes. This allowed bringing the area with transplanted cartilage in direct contact with the tibial plateau (Figure 4), after which the assembly was loaded with forces starting from 0 N to the value leading to a displacement of the cylinders, realising at the same time the acquisition of data concerning the strains in the femur with the Aramis 2M system and the data concerning the compression behaviour of the transplanted cylinders, using the software embedded on the Instron 5587 machine.

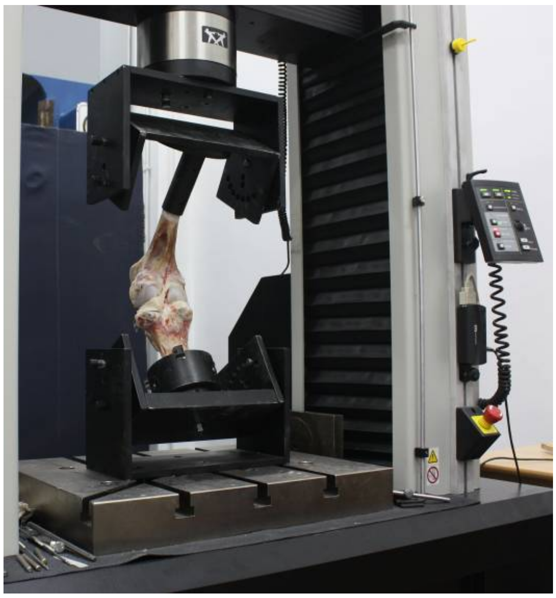


Fig. 4 Fastening of the bovine knee in the Instron machine

With regard to the value of the force which is used for compression, the speciality literature describes several protocols. Due to the viscoelastic characteristics of the cartilage, its strain under pressure depends not only on the applied force, but also on the rate of its application. Most published experiments use a gradual loading, followed by a maintaining of the pressure for a certain amount of time. Thus, Guettler [1] loads gradually up to 700 N and then keeps that pressure for 5 seconds, obtaining the maximal strain during a constant loading at 700 N. Kelly [2] used a loading up to 800 N, while Pena [3] used an axial load of 1,150 N, considering that this value represents the loading during extension of an adult's knee. It is considered that the loading force in extension is of 700 N – 1,150 N, equivalent to the weight of an adult man. Kock used a force of 350 N for the compression of three transplanted cylinders [4]. Nonetheless, the above-mentioned studies were carried out on human knees. Therefore, we can only approximate the bovine loading pressure to about 5,000 N for an animal of 500 kg in unipodal support (improbable for cattle).

Figure 5 presents the graph of compression loading of the knee joint having an osteochondral transplant with cylinders of 8 mm diameter and a length of 20 mm, for an area of the chondral defect of 2.5 cm^2. Although the loading went up to 5,000 N, there were taken into account the values up to the cylinders' displacement.

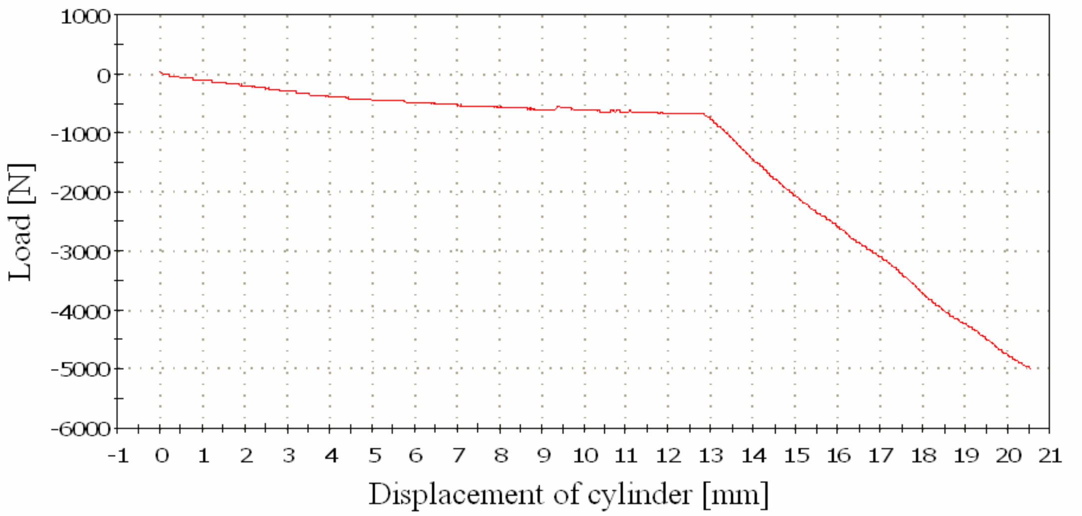


Fig. 5 The variation of force during compressing the femur with a transplanted osteochondral defect (D_{cyl} = 8 mm, A = 2,5 cm^2) with up to 5,000 N

Results and discussions

For modelling, there was used the classical Gauss-Seidel strategy and there was taken into account the force *F* at which the osteochondral cylinder moves inside the receiving tunnel. The previously selected influence factors that were taken into account are: the cylinder's diameter (*d*), the defect area (*A*) and the ratio between the receiving tunnel's length and the length of the osteochondral cylinder (*r*). The 3D graphs from figure 6 present the relationship between the forces at which the transplant moves inside the receiving tunnel and the variation parameters taken into account and mentioned above.

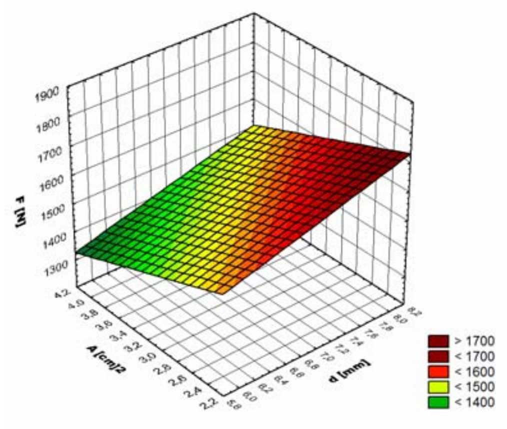
The analysis regarding the variation of the force at which the osteochondral cylinder moves inside the receiving tunnel shows that this force has significant variations function of the parameters that are taken into account.

Also, it can be noticed that all coefficients are significant, so all parameters taken into account influence the model of the force at which the osteochondral cylinder moves inside the receiving tunnel. The strongest influence on the force at which the osteochondral cylinder moves inside the receiving tunnel is exerted by the ratio between the length of the osteochondral cylinder and the length of the reeiving tunnel (*r*), followed by the defect area (*A)* and the cylinder's diameter (*d).*

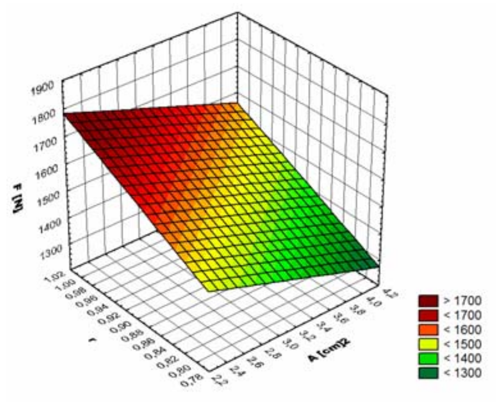
The force at which the osteochondral cylinder moves inside the receiving tunnel increases with the increase towards a value of 1 of the ratio between the the length of the osteochondral cylinder and the length of the reeiving tunnel (*r*), because the osteochondral cylinder rests in this situation also on the tunnel base, but the friction forces between the cylinder and the tunnel wall are larger due to the larger contact area.

Another analysed factor was the area of the chondral defect, which also influences the force at which the osteochondral cylinder moves inside the receiving tunnel, in the sense that the force increases when the area decreases. Applying a force on a certain area creates a pressure that is inversely proportional to the area, which for the case of the osteochondral transplant would mean that a transplant is the more unstable the smaller the transplant area is. In reality, the anatomy and biomechanics of the knee makes this conclusion erroneous. In reality, the loading force does not address only the area of the chondral defect, but also the neighbouring areas with healthy cartilage (which are stable), so that the pressure on the transplanted area is the smaller when the lesion area is smaller.

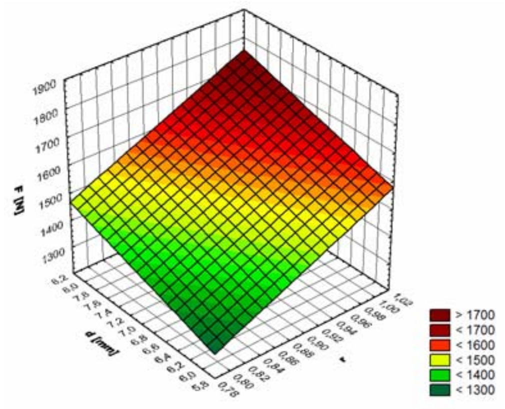
Finally, the cylinder diameter influences the force at which the osteochondral cylinder moves inside the receiving tunnel, in the sense that it increases as the diameter increases.



(a) Variation graph of the force at which the cylinder moves, function of the cylinder diameter and the defect area



(b) Variation graph of the force at which the cylinder moves, function of the depth (length) of the cylinder and the defect area



(c) Variation graph of the force at which the cylinder moves, function of the cylinder diameter and the ratio between the tunnel depth and the cylinder length

Fig. 6 Variation graphs for the force at which the osteochondral cylinder moves inside the receiving tunnel and the variation parameters taken into account

Following the statistical processing of the obtained results and the calculus of the regression coefficients there can be obtained a mathematical model for the analytical calculation of the force at which the osteochondral cylinder moves inside the receiving tunnel (1):

$$F = 287.42 + 74.37 \cdot d - 112.17 \cdot A + 1198.75 \cdot r\,, \qquad (1)$$

It should be mentioned that for determining this polynomial model of 1st order with interactions for the studied force, there was used a factorial programme of type 2^3, using the method of response areas, while the software employed both for this determination and for realising the 3D graphs from figure 6 was Statistica.

Analysis of the relationship between the cylinder length and the depth of the receiving tunnel (r)

In order to analyse the ratio between the cylinder length and the depth of the receiving tunnel and to acquire the reference data, there were run tests on a bovine femur. For this, a fresh bovine femur was used. After deperiostating and removing the ligaments, the bone was degreased. Then, a sagittal cross-section was made at the inner femural condyle. In this cross-section there were carved two receiving tunnels, perpendicular to the joints surface, so that 1/3 of the circumference is outside the realised cross-section (Figure 7). The tunnels have a depth of 15 mm and of 18 mm, respectively.

Fig. 7 Realising the receiving tunnels in the femural condyle

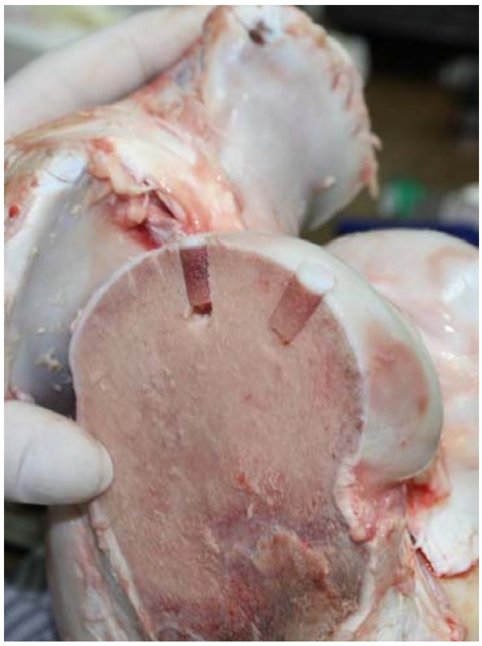


Fig. 8 Positioning of the osteochondral cylinders in the realised defects

After realising the transplants (Figure 8), there were run compression tests on the Instron 5587 machine, in order to determine the strain in the transplants, at forces between 0 and 5,000 N along the axis of the transplanted osteochondral cylinder. In order to determine the stresses and strains in the transplant area, an optical determination method was used, with the help of an optical equipment Aramis 2M which uses two high-resolution video cameras for measuring the displacements of a graphite grid applied on the surface of the femural condyle (Figure 9). In order to acquire the values of strains in the transported cylinders, on the femur there was applied a matte adherent quick-drying paint as well as a grid of "drops" of black paint. After the paint dried, the femur was fastened in the lower component of the device, so that the direction of compression was perpendicular to the axis of the osteochondral cylinder. This required a renewed positioning of the femur in the testing device for each of the two transplanted cylinders.

The first test was run for the case in which the transplanted cylinder does not reach the base of the receiving tunnel, meaning that the resistance to its movement comes only from the friction force between the cylinder and the tunnel. The second test was run for the case in which the transplanted cylinder reaches the base of the receiving tunnel, meaning that the resistance to its movement is due both to the friction force between the cylinder and the tunnel and to the compression applied by the cylinder at the tunnel's base.

Fig. 9 Fastening of the bovine knee in the Instron 5587 machine using the experimental device and positioning of the Aramis 2M system for acquiring the experimental data

The data acquired by the system allowed also analysing following strains and displacements, for various loading pressures: the major strain ε_1, the minor strain ε_2, the equivalent Von Mises strain, as well as the displacements on the Ox axis, the displacements on the Oy axis and the total displacement.

The results obtained for the case in which the transplanted cylinder does not reach the base of the receiving tunnel (Figure 10) show that the displacement on the Oy axis at a loading of 0 N is 0, at 1,000 N it is 0.332 mm, at 2,000 N it is 0.7041 mm, at 3,000 N it is 1.030 mm, at 4,000 N it is 1.424 mm and at 5,000 N it is 2.0901 mm.

The results obtained for the case in which the transplanted cylinder reaches the base of the receiving tunnel (Figure 11), show that the displacement on the Oy axis at a loading of 0 N is 0, at 1,000 N it is 0.1640 mm, at 2,000 N it is 1.9513 mm, at 3,000 N it is 4.8866 mm, at 4,000 N it is de 8.51 mm and at 5,000 N it is 12.07 mm. At 4,000 N and 5,000 N, the maximal displacement on the Oy axis occured at a certain distance from the examined cylinder, on the cylinder it being 7.60 mm and 10.50 mm, respectively.

Conclusions

With regard to calculating the crushing force at the osteochondral cylinders, it can be concluded, from the above results, that the unfolded experiments have a series of limitations. Although this study analyses several parameters that influence the stability and evolution of the autologous osteochondral transplant, several aspects exist that limit the results. The studies were carried out on a static bovine model, that does not allow the assessment of modifications brought on by cyclical loads and thus by all loads that can occur in vivo and also the biological modifications over time cannot be assessed. Also, there have not been assessed the shearing forces occuring in the transplants, the fastening device employed not allowing a translation movement but only a rotation movement, thus altering the articular kinematics. To this come errors pertaining to the surgical technique of carrying out the transplant: a non-parallelism of the cylinders, the perfotion of the bony wall between them, the lack of recovery of the cartilage surface's curvature.

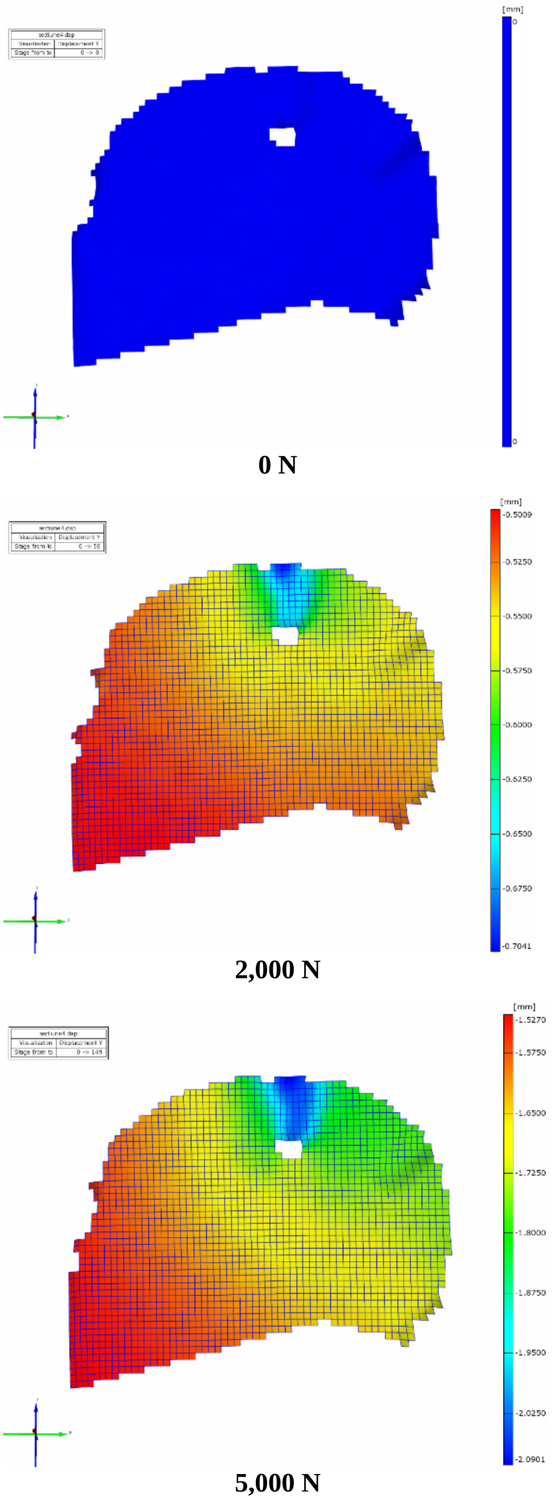


Fig. 10 Displacement on vertical direction (Oy) at the loading of the osteochondral cylinder that does not reach the base of the receiving tunnel

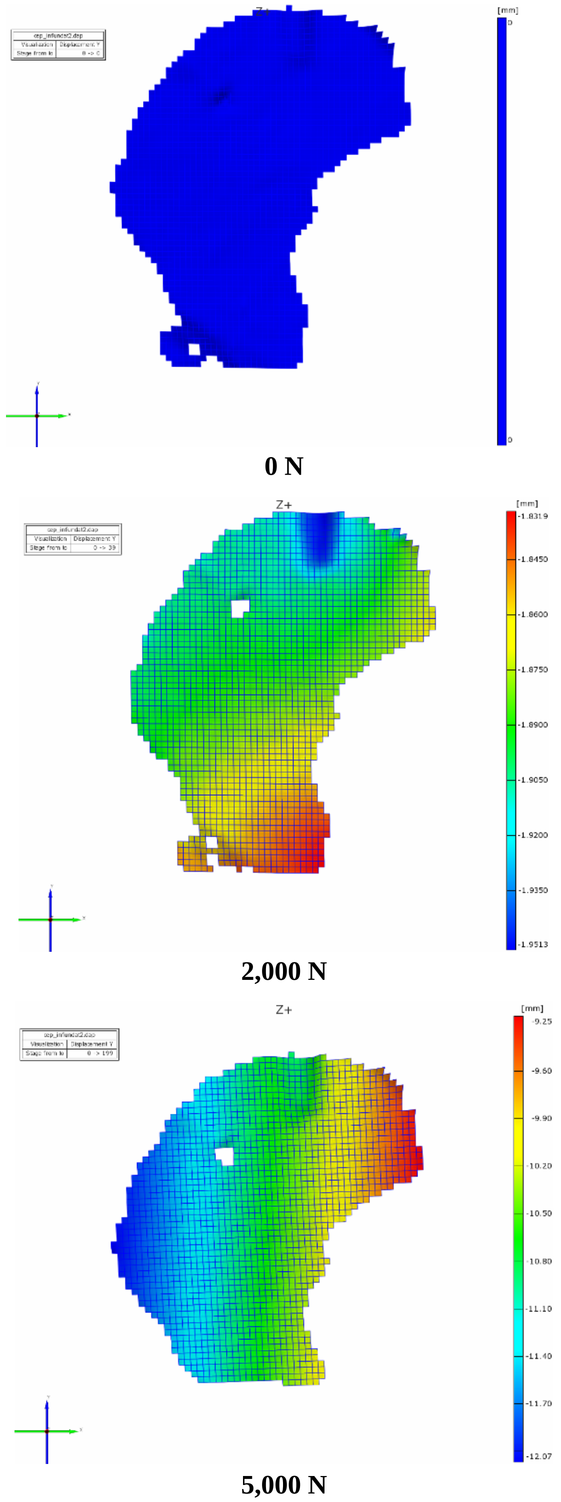


Fig. 11 Displacement on vertical direction (Oy) at the loading of the osteochondral cylinder that reaches the base of the receiving tunnel

A comparative analysis of the results obtained in the two considered situations shows that in the case of the cylinder that does not reach the receiving tunnel's base, the maximal compression strain is reached in the cylinder's walls, while in the case in which the cylinder reaches the tunnel's base, the maximal compression strain is reached at the cylinder's base, showing that the main stabiliser of the cylinder is the friction of the walls, in the first case and the compression at the base, in the second case. Also, at a loading force of 5,000 N, the maximal main strain is of 4.52% for the cylinder that does not reach the tunnel's base, compared with 7.92% in the second case, while the total displacement is of 2.311 mm compared to 11.70 mm. These apparently paradoxical differences are due mainly to experimental errors stemming from the femur's movement in the experimental device, but they do not influence significantly the biomechanical behaviour of the biological material in each considered case.

In the case of the cylinder that does not reach the receiving tunnel's base, the maximal strains occur at the walls (lateral surface of the cylinder) at the interface cylinder-tunnel, towards the cylinder's base, while the maximal total displacement is found on the chondral surface of the cylinder. On the cross-section through the cylinder's axis, there can be noticed significantly larger strains and displacements in the cylinder compared to the rest of the condyle, there existing a step marked by a void area that corresponds to the void space between the cylinder and the base of the receiving tunnel. Also, within the cross-section, the displacement is not even along the cylinder's length, being more pronounced on the Ox axis at the cylinder's base, but with a bipolar aspect, while on the Oy axis - and at the level of the entire displacement - it is more pronounced towards the chondral surface. The maximal main strain is obtained in this case near the cylinder's base, while the maximal secondary strain is obtained on the cylinder's chondral surface, then its value decreases and increases again towards the cylinder's base, without reaching the values from the chondral surface. The maximal equivalent Von Mises strain is obtained at the cylinder's base, having the same bipolar aspect with an increase towards the chondral surface. In all three analyses there appears a void area that corresponds to the void space between the cylinder and the base of the receiving tunnel, in the rest of the condyle the strains being insignificant.

For all parameters analysed in the case of the cylinder that does not reach the receiving tunnel's base there can be noticed a biomechanical behaviour of the cylinder that is conditioned by the behaviour of the cylinder-tunnel interface and that is markedly different from the changes that are found in the rest of the femural condyle.

In the case of the cylinder that reaches the receiving tunnel's base, the maximal main strain is localised on the lateral surface of the osteochondral cylinder, the maximal secondary strain is found at the cylinder's base, while the equivalent von Mises strain has increased values on the contact area between the cylinder and the tunnel, they being larger at the base.

The limitations of the experiment consist in the fact that only one test was run for each type and in the possibility of the result being altered by the presence of both transplanted cylinders in the same femural condyle, in errors at the positioning of the biological part in the experimental device and in the possibility that the cross-section through the condyle was not done exactly at 2/3 of the circumference for each of the two realised tunnels. Nevertheless, the advantage of the employed method is that the same anatomic part is used, with cylinders taken from the same trochlea, ensuring the same mechanical-biological properties in the material used in both experiments.

In conclusion, for the case of the cylinder that does not reach the base of the receiving tunnel, the biomechanical behaviour at axial loading of the osteochondral cylinder is determined by the processes at the interface between cylinder and tunnel, while in the case of the osteochondral cylinder that reaches the base of the receiving tunnel the behaviour of this part at loading is determined mainly by the strains and displacements occuring at the base or near it.

Maybe the most important conclusion of this study is that if in the case of the cylinder that does not reach the tunnel base the analysis shows that the two bodies behave differently under compression, the difference being larger when the loading force is larger, they being interconnected by phenomena at the mantle of the tunnel, in the case when the cylinder reaches the tunnel base the biomechanical behaviour is different, the two bodies behaving like a single unit, the more so as the loading force increases.

Acknowledgments

This work was carried out within the framework of the research grant 698/19.01.2009, supported by the Romanian Ministry of Education and Research and the National Council for University Research.

References

1. Guettler, J.H., Demetropoulos, C.K., Yang, K.H. and Jurist, K.A., Osteochondral Defects in the Human Knee, *The American Journal of Sports Medicine*, 32(6), pp 1451-1458, 2004;
2. Kelly, D.J., Prendergast, P.J., Mechano-regulation of stem cell differentiation and tissue regeneration in osteochondral defects, *Journal of Biomechanics*, 38, pp 1413-1422, 2005;
3. Pena, E., Calvo, M., Martinez, M., Doblaré, M., Effect of the size and location of osteochondral defects in degenerative arthritis, *A finite element simulation Computers in Biology and Medicine*, 37(3), pp 367-387, 2007;
4. Kock N. B., Smolders J. M. H., van Susante J. L. C., Buma P.,van Kampen A., Verdonschot N., A cadaveric analysis of contact stress restoration after osteochondral transplantation of a cylindrical cartilage defect, *Knee Surg Sports Traumatol Arthrosc*, 16, pp 461–468, 2008.

Studiul experimental asupra comportării cilindrilor osteocondrali transplantați la nivelul condilului femoral în cazul unui transplant osteocondral autolog

Rezumat

În lucrarea de față este prezentată o analiza experimentală a unui genunchi de vită având un transplant osteocondral autolog la nivelul unui condil femural urmăreşte evaluarea comportamentului cilindrilor transplantați la presiune. Determinările experimentale se vor realiza pentru diferite diametre ale cilindrilor şi pentru diferite suprafețe ale leziunii condrale. Se va utiliza un stand de concepție proprie, precum şi sistemul Aramis de măsurare a deformaților. Scopul acestui studiu este de a determina dacă solicitarea mecanică a cilindrilor transplantați determină deplasarea acestora (înfundarea), cu compromiterea rezultatului biologic şi funcțional al transplantului.