Acta of Bioengineering and Biomechanics
Vol. 10, No. 4, 2008

Mechanical properties of temporomandibular joint disc on the basis of porcine preparation investigations

WIESŁAW CHLADEK, ILONA CZERWIK*

Department of Process Modelling and Medical Engineering, Silesian Polytechnic University, Katowice, Poland.

The paper presents the results of a study on mechanical properties of porcine temporomandibular joint discs. Taking into account anatomical properties, three typical spots were selected for the investigation: the posterior, anterior and central parts of the disc. The main focus was on the influence of samples' preparation on the changes in mechanical properties. Complete undamaged discs, cylindrically-cut disc samples of 5 mm in diameter as well as discs of locally broken continuity in the upper layer around the measuring zone were prepared. Periodic compression was applied during testing, by varying the force in a sawtooth control signal. The rate of increasing the force applied equalled 1 N/s with a maximum value of 3 N. Based on the stress and strain characteristics obtained, the object's rigidity, Young's modulus of the samples, and effective Young's modulus of joint discs were calculated. Results showed that the stress and strain characteristics of the discs' substance depend on sample preparation, measurement location and load history within a given number of cycles. Only the fifth load cycle may be considered as stabilized. The most rigid proved to be the posterior part of the disc, as the rigidity of the samples, of an incised disc and of a complete disc in the fifth loading cycle amounted to 117.9 N/mm, 88.8 N/mm and 87.1 N/mm, respectively. A central part of the disc exhibited the lowest rigidity, whose values for the samples, for an incised disc and for a complete disc reached 87.9 N/mm, 70.6 N/mm, and 38.7 N/mm, respectively. Excision of the samples resulted in their dehydration, which led to increased rigidity, as reflected by Young's modulus values. In the posterior part of the disc, the modulus value was 12.56 MPa, while in the anterior part and in the center, these values reached 7.25 MPa and 6.99 MPa, respectively. Excised discs also exhibited dehydration effects during examination. While loading complete discs, the lowest effective values of Young's modulus were obtained, despite the influence of the tissues adjacent to the loaded zone, counteracting deformation. The values were 4.44 MPa, 1.97 MPa and 2.99 MPa for the posterior, central and anterior parts, respectively. Present data allow the conclusion that the error introduced due to breaking the tissue continuity is greater than the error resulting from ignoring substance continuity when applying local loads to an undamaged disc. Therefore, it seems more sensible to adopt the effective Young's modulus values in numerical analyses rather than to apply the results obtained for the samples cut out of discs.

Key words: *joint disc, temporomandibular joint, rigidity, modulus of elasticity, load, preparation, samples*

1. Introduction

Contemporary medicine faces an alarming number of cases with temporomandibular joint pathology, whose diagnosis is possible by monitoring the changes in the joint's working mechanism. A right diagnosis is based on the disorders of the trajectory of mandible movements and on acoustic symptoms of mandible injuries. Magnetic resonance images and computed tomography are usually sufficient to examine mechanical function and to provide efficient therapeutic methods [1], not to mention prophylaxis. Clinical experiments show that the main causes of the joint dysfunction are psychomotor conditions, parafunction and asymmetry of load imposed on alveolar arch caused by occlusal abnormalities or dental defects. However, clinical observations are not sufficient to find an explicit relation between causes and effects, including disc displacement or perforation. The causes

---

* Corresponding author: Ilona Czerwik, Department of Process Modelling and Medical Engineering, Silesian Polytechnic University, ul. Krasińskiego 8, 40-019 Katowice, Poland. E-mail: ilona.czerwik@polsl.pl or i_czerwik@interia.pl

Received: April 21st, 2008
Accepted for publication: December 10th, 2008

lie in the phenomena connected with forces and stress distribution in joint components, which cannot be clinically diagnosed. Therefore, biomechanical tools are considered virtually indispensable for a full explanation of these issues. The proper diagnostic methods are model analyses based on numerical methods, such as the finite element method. The compatibility between the calculation results and the state of a natural object depends on approved boundary conditions, particularly on a correct definition of the material properties of the system investigated. Therefore, gathering data on the material has a paramount importance, since it is hard to imagine a correct numerical simulation of the mechanical states in a living organism. Common awareness of this fact encourages numerous researches endeavoring to determine the properties of natural tissues responsible for transferring forces during a person's physical activities. For the temporomandibular joint, the key issue is to determine the properties of the joint disc tissues while considering the variety of features represented by its particular fragments. However, available data on joint discs differs considerably, and in many cases is questionable, due to both the research material preparation and the measuring techniques [2]. This paper attempts to show how excising joint disc samples can influence their mechanical characteristics. Our experiments conducted on porcine temporomandibular joint discs were preceded by initial tests whose aim was to find whether the results obtained could be relevant to human joint discs.

2. Methods

The porcine samples were used for laboratory tests due to the similarity between chewing mechanisms in humans and pigs. The human and porcine discs shown in figure 1 illustrate a similar diversity in their tissue thickness. Disc thickness and penetration depth of a ball penetrator of 5-mm diameter, indented using the force of 1.2 N for 15 s, were measured with 0.01 mm accuracy to reveal the similarity between both samples. The percentage ratio of penetrator indentation to disc thickness in the spot investigated was used as the basis for evaluation. Considering the possibility of taking samples later in the experiment, the places marked in figure 1 were selected for analyses in the posterior (P), anterior (A) and central (C) parts. Preliminary investigation was carried out for four porcine and two human discs taken from a 67-year old donor.

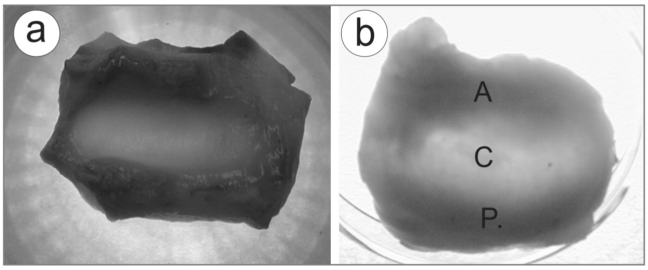

Fig. 1. View of porcine (a) and human (b) discs in transmission light with marked places of measurements: A – anterior, P – posterior and C – central spots

Using the Zwick universal strength-testing machine with a 25 kN load range, controlled by the TestXpert program, the basic mechanical features were determined. There were prepared cylindrical samples of 5-mm diameter, whose view and incising method are shown in figure 2: complete undamaged discs and discs with locally broken tissue continuity around the zone of measurement.

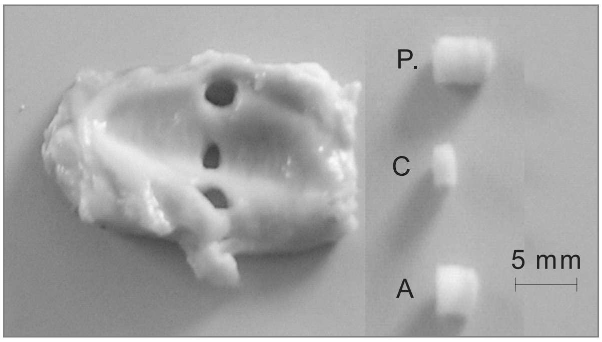

Fig. 2. Sampling places and view of cut-out samples

The breaking of the tissue continuity was accomplished by making four symmetrically distributed shallow incisions located on the sides of a square within a ca. 1-mm distance from the place of punch adhering to the disc surface. The 2-mm long incisions were not joined together and their total length did not exceed 1/3 of the square's perimeter. Such a procedure was meant for "scattering" the measurement zone, thereby for minimizing the influence of tissue damage on the rigidity of the object investigated. During preparation, the thickness of the measurement zone was determined each time, as it was the initial dimension for determining a relative deformation. Additionally, prior to mechanical tests, the samples cut out of discs were weighed with the accuracy of 0.0001 g. During testing, the samples were placed in an hole cut out in a layer of loosely-stacked blotting paper to allow absorption of the flowing fluid, without disturbing the process of loading and deformation. Weighing was repeated after mechanical tests to estimate the quantity of the fluid exuded.

The following devices were used to impose a direct pressure on the samples:

- flat punch, 5 mm in diameter, used for the samples cut out of the disc's central part and in order to apply pressure in the central part of the complete disc;
- punch, 5 mm in diameter, of the shape of pressure surface similar to that of the disc parts tested; it was used for compressing cylindrical samples taken from anterior and posterior parts of the disc as well as for loading these zones on a complete disc.

Adjustment of the punch shape to the disc circumferential structures prevented the disc from slipping and reduced errors resulting from difficulties in obtaining a uniform geometry for the front surfaces of the samples.

After an appropriate placement of the sample in relation to the punch, ten compression and relaxation cycles were applied with adopting a sawtooth control signal of the force–time characteristics at a constantly increased loading rate of 1 N/s. Cycles with the force from zero to 3 N were applied. The maximum threshold loads were predetermined in initial tests so as to avoid crushing the disc tissues during the first cycle. For the load range adopted, the reshaping of deformed tissues after the first cycle occurred within approximately 110 seconds. Thus, in practice, while using the timeframes adopted, a slight disc load was present in the lower ranges of the cycle, ensuring contact between the tissues and the punch.

3. Results

The results of preliminary comparative studies of human and porcine discs are juxtaposed in table 1, presenting average thicknesses and relative indentation depths, determined as a relationship between the penetrator's indentation depth and disc thickness within the area under examination.

Table 1. Thicknesses of human and porcine joint discs and their relative deformations under spot pressure

The spot	Thickness (mm)		Penetrator's relative indentation (%)	
	Human disc	Porcine disc	Human disc	Porcine disc
A	2.7	2.9	6.3	4.9
P	3.2	4.4	4.1	4.2
C	0.9	1.3	12.3	9.7

Thickness measurements indicate that, despite a larger mass of the porcine disc, its shape is similar to that of the human disc. Both human and porcine discs display strengthening of anterior and posterior parts, with the posterior part being thicker and more rigid than the anterior one. The central and side parts of the disc are substantially thinner and more sensitive to loads, as shown by the relative deformation analysis. The proven similarity was considered sufficient to use a porcine disc for further research, with the prospect of utilizing the present results in a future model study of human joint components.

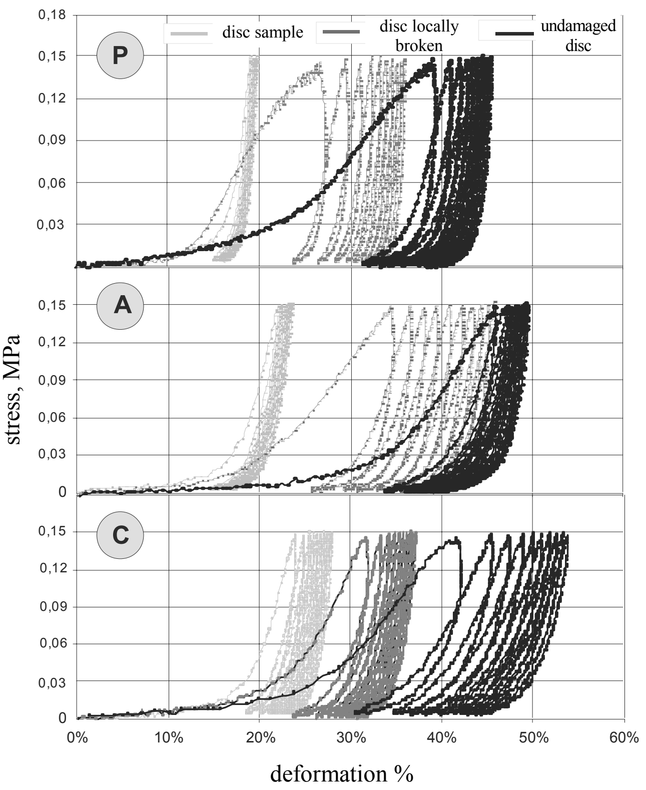

Fig. 3. Examples of stress and deformation characteristics obtained for P (posterior), A (anterior) and C (central) parts of a disc for: cut-out samples, a disc whose tissue continuity is broken and for a complete, undamaged disc

The force-deformation characteristics were recorded during tests performed with a strength tester. To make the analysis easier, the data was presented in the form of plots of stress and relative dimensionless deformation. The size diversity of the discs tested can be useful in such procedures. The thicknesses of the disc's central part fell between 0.9 and 1.4 mm, the anterior part – between 2.0 and 3.4 mm, and the posterior part – between 3.4 and 4.5 mm. Plotting graphs with the deformation values, expressed in millimeters shown on the axis, makes the comparison much more difficult. Nine representative cases presented in figure 3 were chosen from the plots featuring the measurement spot and the sample preparation technique.

In all cases, the time necessary for a full elastic recovery was substantially longer than the cycle duration, illustrated as a "cyclic pseudo-creep" effect in the figure. The fastes elastic recovery occurs when the tissue continuity is not broken. In each case, the cut-out samples showed the least total deformation.

The discs incised in the anterior and posterior parts featured an enhanced, intensive "cyclic pseudo-creep", which can be explained by a fluid exudation. The undamaged discs maintained the greatest deformation potential and showed a moderate pseudo-creep effect. Where the disc's central part displayed the least thickness, incisions were relatively deep, creating characteristics similar to those in an excised sample, which could also be explained by fluid exudation.

The basic result of examination was the rigidity of the objects under investigation, calculated using the ratio of pressure force to displacement $F/\Delta l$, and σ/ε quotient determined from linear fragments [3] of hysteresis sections of the first, fifth and tenth test cycles. Complementary information, illustrating the dissipation processes, refers to the total deformation range for the cycle $\Delta\varepsilon_c$ and the deformation $\Delta\varepsilon_d$ characterizing the width of hysteresis loop; also, the percentage weight loss of a sample caused by fluid exudation was determined. Weight changes were analyzed exclusively for the excised samples, for which σ/ε quotient corresponded to Young's modulus. An identical rigidity and the calculation technique of σ/ε quotient were applied to complete discs, although inner forces, which increase disc resistance to local deformation, affect the results. Thus, σ/ε values provided for complete discs may be treated as an estimated effective Young's modulus, comparable to the Young's modulus determined for the incised samples. It should be mentioned that an attempt to calculate the effective Young's modulus was made as well, by adopting the methods described in [4], [5]. Yet, the results were almost ten times lower than the experimental ones and, consequently, deemed completely erroneous, thus rejected as useless for publication. Table 2 presents the experimental results, being the average

Table 2. Average rigidity values, ranges of deformation, elasticity modulus and percentage weigh loss of cut-out samples

Spot examined	Sample type	Cycle number	Rigidity (N/mm)	Deformation range in cycle $\Delta\varepsilon_c$ (%)	Hysteresis loop width $\Delta\varepsilon_d$ (%)	Quotient σ/ε (MPa)	Range of changes in sample's weight loss (%)
Posterior part of disc	Sample's graph	1	63.7	18.9	1.6	9.12	8–11
		5	117.9	3.7	0.6	12.56	
		10	147.5	3.6	0.5	15.92	
	Incised disc	1	23.4	26.6	12.1	1.19	–
		5	88.8	3.8	1.2	4.53	
		10	139.5	3.2	0.9	7.11	
	Complete disc	1	17.3	39	14.8	0.88	–
		5	87.1	7.8	2.5	4.44	
		10	97.4	6.2	1.4	4.96	
Anterior part of disc	Sample's graph	1	56.4	21.6	2.3	4.9	8–14
		5	97.3	6.4	0.8	7.25	
		10	116.9	6.3	0.6	7.93	
	Incised disc	1	19.9	34.5	11.4	1.02	–
		5	64.3	8.1	2.8	3.28	
		10	75.7	7.3	1.7	3.86	
	Complete disc	1	21.5	45.6	9.8	1.09	–
		5	58.8	11.4	2.9	2.99	
		10	62.7	9.3	2.4	3.19	
Central part of disc	Sample's graph	1	48.7	23	8.6	2.28	15–28
		5	87.9	4.7	1.6	6.99	
		10	103.5	3.9	1	8.24	
	Incised disc	1	31.9	33.6	8.5	1.62	–
		5	70.6	7.6	1.4	3.6	
		10	90.1	6.8	1.1	4.59	
	Complete disc	1	21.4	44.2	11	1.09	–
		5	38.7	11.1	2.7	1.97	
		10	46.2	9.53	1.8	2.35	

value from three measurements made on tissues sampled from different animals.

Table 2 does not provide any information about the "scatter" of results, since the average values were calculated only for similar, regular hysteresis loops with errors smaller than 7%. Significant differences were found only in the first load cycle, where the range of deformation $\Delta\varepsilon_c$ corresponds to the total distance of the punch being in a full contact with the sample and reaching the maximum cycle force. In this case, a relative error reached 30%.

4. Discussion

Despite numerous attempts, the issue of identifying the mechanical properties of a temporomandibular joint disc has never been fully recognized, as shown by the "scatter" of Young's modulus values [2] provided by professional literature and the selection of the objects under analysis. Due to ethical constraints, human discs are rarely investigated [6]–[8], and most experiments are carried out using the discs of such animals as dogs, cows or pigs [9]–[11]. Sample preparation techniques and load conditions vary, which affects the results. The range and speed of the load applied as well as the disturbance of the natural hydro-mechanical state of tissues raise most objections. The most significant deviations from the natural state concerns the results obtained for the samples excised from different disc zones and investigated at a low speed of load increase [7], where Young's modulus reached 0.211 and 0.541 MPa. Such results are significantly lower than those reported in professional literature, where the modulus values fluctuate between 6 and 30 MPa. Since a fluid level in the tissue changes, the samples were excised with a hot blanking die, which allowed a crust to be formed on the incised surfaces [12]. Yet, even if such a method is applied, a local dehydration of tissues is unavoidable.

The experiments also focused on strength problems, because the tests conditions differed significantly from those in temporomandibular joints [13]. The mechanical conditions in these joints can be evaluated in model research, but the correctness of the solutions obtained depends on the credibility of data on the material. A significant diversity in disc tissue properties presented in some papers [9], [14] may be justified by the mechanism of disc adjustment to the acetabular cup of a changeable shape when the head of a condylar process passes from the lower jaw onto the nodule. Thicker peripheral fragments, that can transfer a greater load, act as main support points; the flexible central part works as a membrane, separating the upper and lower parts of the joint and, due to its elasticity, it facilitates a proper force distribution in the bone parts of joints. Such a behaviour of the disc is ensured by the structure of bone tissue in a lower part of the mandibula. The central part of the lower mandibula is the thinnest and hence not adjusted to transfer high stresses [15]. As a result of ignoring such facts, a false pattern of stress distributions in joints is developed, the pattern that shows the stress concentration in the central parts of the joint [16]. Similarly, introducing averaged data to the whole model of disc [17] limits the understanding of its real role in joint functioning.

In our study, we hope to show that the stress and deformation characteristics, while examining the discs, depend on sample preparation, the spot of measurement and the load history determined by the number of cycles. Based on the characteristics obtained for incised samples, it can be inferred that such samples are more rigid than those obtained when loading the disc, irrespective of the sampling spot. If we take into account the fact that the cohesion forces, generated if a disc is locally loaded, should result in increased rigidity, we may arrive at a clear hint enabling appraisal of the compatibility between the results obtained and the object's true behaviour. We believe that the excision of samples generates the results with a more considerable deviation from reality than an approximate determination of the effective Young's modulus on a completely undamaged disc. Based on the results presented in table 2, we can infer that the values of Young's modulus should be diversified in numerical calculations with regard to particular fragments of the disc model, assuming 4.46–4.96 MPa for the posterior part, 1.97–2.35 MPa for the central part and 2.99–3.19 MPa for the anterior part. It is obvious that obtaining a complex behaviour pattern of the loaded joint requires further investigation. Each change in the test parameters will affect the results, e.g. an increased deformation rate will inevitably result in increased rigidity and Young's modulus. Therefore, the speed and range of load should be adjusted to a particular patient subjected to surgery, with a special attention paid to the load conditions in persons with joint dysfunctions [1]. It can be expected that, in spite of some changes in the values of particular parameters, the essence of diversity of the mechanical properties of the disc's individual fragments will be maintained. The factors analyzed build a logical system enabling the formulation of the following generalized conclusions:

- In each case, the rigidity of the sample investigated increases with the number of cycles.
- The peripheral structures of disc are definitely more rigid than the central ones, with the posterior part being the strongest.
- An enabled fluid loss results in increased disc rigidity, which is reflected in Young's modulus values.
- The disc centre is its most flexible part in spite of the loss of the greatest quantity of fluid after a sample has been cut out of the disc.

The methodology of determining the elasticity moduli for the lateral and central segments on the disc circumference remains an unresolved issue. Small sizes and irregular shapes of the segments obstruct a credible experiment. By the time the necessary data is experimentally determined, it seems most reasonable to adopt, for numerical models, the properties of those areas which are consistent with the posterior part of a disc.

5. Conclusions

- The procedure of preparing a material for tests has a great influence on mechanical properties of temporomandibular joint discs.
- The results obtained allow us to conclude that when testing elasticity, a greater error arises from breaking the tissue continuity than from disregarding the influence of material continuity when locally loading an undamaged disc.
- The excision of samples results in an overestimation of the elasticity modulus values and therefore it seems that adopting the effective Young's modulus in numerical analyses is more sensible than using the results obtained for the excised samples.
- Due to variability of the characteristics during consecutive load cycles, the disc properties identified in a typical static compression test should not be taken into account in a model examination of joint load.
- Only the fifth load cycle may be considered as stabilized. This is characteristic of this cycle that it should be the basis for evaluating the joint disc's elasticity.

References

[1] OKESON J.P., *The treatment of mastication organ dysfunction and occlusion disorders*, Czelej, Lublin, 2005.

[2] TANAKA E., EIJDEN T., *Biomechanical behavior of temporomandibular joint disc*, Critical Reviews in Oral Biology and Medicine, 2003, 14(2), 138–150.

[3] MOV V.C., HUISKES R., *Basic Orthopaedic Biomechanics and Mechano-Biology*, Lippincott Williams and Wilkins, 2005.

[4] ZHANG M., ZHENG Y.P., MAK A.F.T., *Estimating the effective Young's modulus of soft tissues from indentation tests–nonlinear finite element analysis of effects of friction and large deformation*, Medical Engineering and Physics, 1997, Vol. 19, 512–517.

[5] DELAFARGUE A., ULM F.J., *Explicit approximations of the indentation modulus of elastically orthrotropic solids for conical indenters*, International Journal of Solids and Structures, 2004, 7351–7360.

[6] FONTENOT M.G., *Viscoelastic properties of human TMJ discs and disc replacement materials*, Journal of Dental Research, 1985, 64–163.

[7] CHIN L.P.Y., AKER F.D., ZARRINNIA K., *The viscoelastic properties of the human temporomandibular joint disc*, Journal of Oral and Maxillofacial Surgery, 1996, 54, 315–318.

[8] TANAKA E., SHIBAGUCHI T., TANAKA M., TANNE K., *Viscoelastic properties of the human temporomandibular joint disc in patients with internal derangement*, Journal of Oral and Maxillofacial Surgery, 2000, 58, 997–1002.

[9] TANNE K., TANAKA E., SAKUDA M., *The elastic modulus of the temporomandibular joint disc from adult dogs*, Journal of Dental Research, 1991, 70, 1545–1548.

[10] TENG S.Y., XU Y.H., CHENG M.H., LI Y., *Biomechanical properties and collagen fiber orientation of TMJ discs in dogs*. Part 2. *Tensile mechanical properties of the discs*, Journal of Craniomandibular Disorders: Facial and Oral Pain, 1991, 5, 107–114.

[11] BEATTY M.W., BRUNO M.J., IWASAKI L.I., NICKEL J.C., *Strain rate dependent orthotropic properties of pristine and impulsively loaded porcine temporomandibular joint disc*, Journal of Biomedical Materials Research, 2001, 57, 25–34.

[12] ALLEN K.D., ATHANASIOU K.A., *Viscoelastic characterization of the porcine temporomandibular joint disc under unconfined compressions*, Journal of Biomechanics, 2006, 312–322.

[13] LAI W.F.T., BOWLEY J., BURCH J.G., *Evaluation of shear stress of the human temporomandibular joint disc*, Journal of Orofacial Pain, 1998, 12, 153–159.

[14] POZO R., TANAKA E., TANAKA M., OKAZAKI M., TANNE K., *The regional difference of viscoelastic property of bovine temporomandibular joint disc in compressive stress–relaxation*, Medical Engineering and Physics, 2002, 24, 165–171.

[15] CHLADEK W., KRASIŃSKI A., KASPERSKI J., *Krążek stawowy jako element redukujący naprężenia stykowe*, Protetyka Stomatologiczna, Warszawa, 2002.

[16] IWASAKI L.R., NICKEL J.C., MCLACHAN K.R., *Relationship Between Growth Function and Stress in the Temporomandibular Joint*, Science and Practice of Occlusion, Quitessence, Hong Kong, 1997, 125–37.

[17] BEEK M., KOOLSTRA J.H., RUIJVEN L.J., EIJDEN T.M.G.J., *Three-dimensional finite element analysis of the human temporomandibular joint disc*, Journal of Biomechanics, 2000, 33, 307–316.