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EFFECT OF SUPPORT ON MECHANICAL PROPERTIES OF THE INTERVERTEBRAL DISC IN LONG-TERM COMPRESSION TESTING

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The complex kinematic structure and the method of support of the spinal motion segments significantly influence mechanical properties of the intervertebral disc (IVD). Because of this, the aim of this study was to analyse the effect of support of the spinal motion segment on selected mechanical properties of the intervertebral disc. The research involved two groups of study: with intact segments (IS) and with acutely injured segments (AIS). In a long-term cyclic compression test, the spinal segments were loaded with a force of 150-650 N. The study has shown that in the case of damage to articular processes, intervertebral disc height decreases by 0.09 mm, and this decrease is 50% greater than in the case of intact segments. The most significant increase in the stiffness coefficient, greater by 63% in the case of injured segments, occurs after 50 000 cycles, which leads to pathological changes taking place in the structure of annulus fibrosus. In assessing the mechanical properties presented in this study, we should bear in mind that this is not a description of the properties of the intervertebral disc alone but also of the elements working with it.

Keywords: spine, intervertebral disc, cyclic loading, viscoelastic properties, energy dissipation

1. Introduction

The complex structure of the spine enables performance of different movements while transferring loads during daily activities. The basic unit of the spine that enables execution of these tasks is the motion segment, which consists of two rigid bony blocks connected by an intervertebral disc. The multiplanar range of motion of the spine is possible thanks to, among others, a three-point support (intervertebral disc and two symmetrical facet joints), which transfers loads acting on the spine. Specifically, axial loads are transferred to a greater extent by the intervertebral disc than by articular processes (Nachemson, 1960; Ranu,1990). In the case of a healthy spine, the posterior column (articular processes) transfers 5-10% of the load. This value increases with the development of degenerative changes in the intervertebral disc. In such a case, the processes can take over up to 40% of the load (Pollintine *et al.*, 2004). At the same time, the combination of flexion-extension movements, twisting and shearing of the segments directly affects the mechanics of the intervertebral disc showing viscoelastic properties (Stokes *et al.*, 2002; Gadd and Shepherd, 2011; Żak and Pezowicz, 2012; Izambert *et al.*, 2003; Campana *et al.*, 2011).

Many authors emphasize that the method of support of the motion segments has a significant impact on kinematics of the spine and mechanical properties of the intervertebral disc (Rohlmann *et al.*, 2006; Robertson *et al.*, 2013). However, these results are obtained by static tests, which, although important for understanding the disc mechanics, do not reflect the conditions characteristic for long-term repeating loads acting on the spine.

Consequently, these studies do not explain how biomechanical behaviour of the intervertebral disc changes in a long-term compression test that corresponds to a load contributing to, among others, the formation of pathological changes in the spine.

Only a few authors have analysed the impact of cyclic loading (above 20 000 cycles) on the biomechanics of the intervertebral disc, including its viscoelastic properties, change in stiffness and energy dissipation (Johannessen *et al.*, 2004; Koeller *et al.*, 1984; Hasegawa *et al.*, 1995; Schmidt *et al.*, 2010). However, these works focused mainly on the analysis of the impact of the applied test protocol (cyclic loading, creep, recovery) in the axial compression test on the mechanical properties of the disc. Moreover, the analyses involved only the motion segments with articular processes removed. Such a procedure enables description of the phenomena taking place in the intervertebral disc but the adopted test system differs significantly from the actual system, in which the posterior pillar plays equally important role in the transfer of loads as the anterior column.

Based on the above, the aim of this work was to determine the impact of the three-point support in spinal motion segments on the mechanical properties of the intervertebral disc in compression testing. The analysis of the mechanical properties of the intervertebral disc was performed on the obtained hysteresis loops, determining, as one of the parameters, changes in energy described by dissipation energy (Wilke *et al.*, 1998; Żak and Pezowicz, 2013; Gardener-Morse and Stokes, 2003).

2. Material and method

The tests were performed on the motion segments collected post mortem from six thoracic spines of domestic pigs aged 8-9 months and weighing 90-110 kg. Currently, the research on models of human preparations (cadaver) is replaced by preparations of animal origin. For studies of the spine (particularly the intervertebral disc) to the most commonly used animal species include: pigs, sheep, dogs, rabbits, mice and rats. There are many reasons indicating that the animal model of the spine is not equivalent to the human spine. However, despite many differences, the authors of in this study prove that the animal preparations of the spine can replace the models of the human spine (Szotek *et al.*, 2004; Alini *et al.*, 2008; Lotz, 2004). The selected segments Th8-Th11 were divided so that they formed the basic functional unit of the spine: vertebra-intervertebral disc-vertebra. Since the main objective was to analyse the impact of the spinal support column, the segments were divided into two groups: IS-intact segments $(n = 5)$ prepared in such a way as to preserve all supporting elements of the spine (anterior and posterior columns), and AIS-acutely injured segments $(n = 5)$ after removal of the load-bearing elements of the spine in the posterior column (Fig. 1). Next, the motion segments were stored in plastic containers at $-20°C$ until testing. Because hydration has a significant impact on mechanical properties of the intervertebral disc (Żak and Pezowicz, 2013), the spinal motion segments were defrosted at room temperature and then hydrated in NaCl saline environment for one hour.

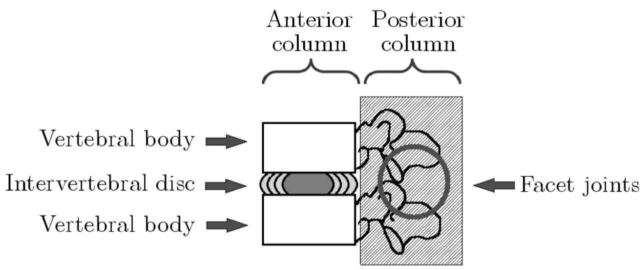

Fig. 1. Schematic diagram of functional spine segments: IS-intact segments (with anterior and posterior columns), AIS – acutely injured segments (anterior column only). The motion segment consists of the intervertebral disc located between two vertebrae. The anterior column consists of two vertebral bodies and an intervertebral disc, whereas the posterior column is formed by articular processes of the vertebrae and ligaments

The vertebral bodies of the segments were fixed with screws to the upper and lower brackets of a purpose-built test system (Fig. 2). The bone parts of the segments were mounted in a bracket at one third of the height of the vertebral body. The test system was also equipped with an element enabling forced physiological bending of the segments during the test at a 6° angle (Dunlop *et al.*, 1984; Dolan and Adams, 2001; Callaghan and McGill, 2001). This loading method, i.e. compression with bending, leads to faster induced failure in intervertebral disc structures (Adams and Dolan, 1996).

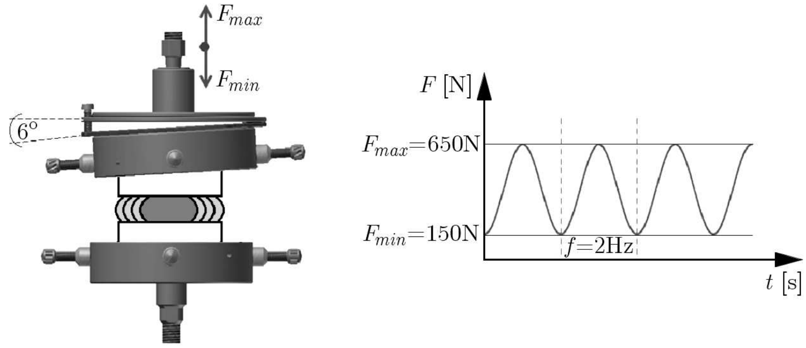

Fig. 2. Diagram of the motion segment mounting in the test rig with simulated progress of the process of loading segments during the test

Daily loads acting on the spine were simulated on an MTS 858 Mini Bionix testing machine. The test was performed for 100 000 loading cycles at a frequency of 2 Hz. The segments were loaded with an axial force between 150 N to 650 N, which simulated daily range of loads put on the spine. It was also assumed that the first 50 cycles corresponded to conditioning cycles (Żak and Pezowicz, 2013; Żak, 2010). At the same time, during the whole compression test, the segments were hydrated with saline solution through the superior vertebral body (Huber *et al.*, 2007). This forced physiological flow of the fluid through the intervertebral disc structure, eliminating the effect of dehydration on the obtained mechanical parameters (McMillan and Adams, 1996; Stokes *et al.*, 2002). In addition, in order to prevent drying of the external soft tissues, the specimens were wrapped in moist gauze.

The effect of cyclic axial loads on the structure of the tested motion segments (IS, AIS) was determined from the force-displacement curves of the specimens compressed with a force of 150-650N – see Fig. 3.

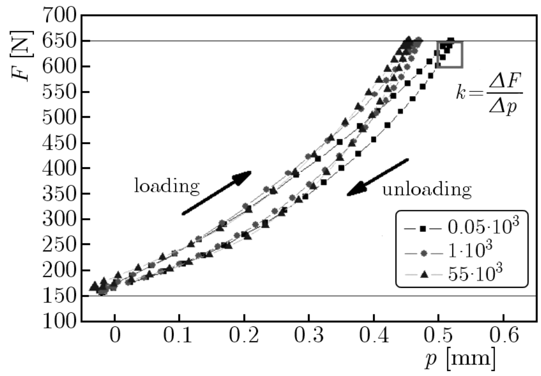

Fig. 3. Exemplary $F(p)$ function for an intact motion segment obtained in compression testing: typical data of selected hysteresis loops. Stiffness coefficient (k) was determined at the maximum force intervals during unloading

Changes in the IVD height for successive hysteresis loops were determined according to Eq. (2.1) on the basis of changes in the segment displacement at the minimum and maximum loads

$$\Delta h = p_{F\,max} - p_{F\,min} \tag{2.1}$$

where Δh [mm] are the changes of the IVD height, $p_{F\,max}$ [mm] – displacement at the maximum load, $P_{F\,min}$ [mm] – displacement at the minimum load.

The stiffness coefficient was determined according to Eq. (2.2) on the basis of the displacement at a range of load 630-650 N. It was to correspond with stiffness values obtained at the maximum load (Fig. 3)

$$k = \frac{\Delta F}{\Delta p} \tag{2.2}$$

where k [N/mm] is the stiffness coefficient, ΔF [N] – the range of load 630-650 N, Δp [mm] – displacement at loads 630-650 N.

The obtained hysteresis loops of the area enclosed by the load-displacement curve were used to assess the degree of damping of the tested spinal motion segments, defined as dissipation energy ΔE determined based on the difference between the surface area during loading E_L and unloading E_U, according to Eqs. (2.3)

$$\Delta E = E_L - E_U \qquad E_{L,U} = \int\limits_{F_{min}}^{F_{max}} F(p)\,dp \tag{2.3}$$

where ΔE [J] denotes the dissipation energy, $E_{L,U}$ [J] – area of half hysteresis in function $F(p)$: L – loading, U – unloading.

According to the study by Koeller *et al.* (1984), the balance of energy changes in successive hysteresis loops can be used to determine viscoelastic properties of the intervertebral disc. The authors presented a method for determining material properties, in which the ratio of dissipation energy to energy obtained in a loading half cycle defines the so-called viscoelastic factor VEF

$$VEF = \frac{\Delta E}{E_L} \tag{2.4}$$

where VEF [–] is the viscoelastic factor, ΔE [J] – energy dissipation, E_L [J] – area in loading.

The viscoelastic factor can be used to determine whether a material has mostly elastic or viscous properties. When VEF is close to 0, the material shows more elastic properties. However, when VEF approaches 1, the material shows more viscous properties.

3. Results and discussion

The values of mechanical parameters, determined in cyclic load testing of specimens, showed differences between successive cycles and between the examined groups of motion segments of the spine. Figure 4a shows a decrease in changes of the IVD height in successive cycles. In the case of both IS and AIS segments in the course of Δh, we can distinguish two characteristic stages: first – an initial, dynamic drop in height; and second – stabilization, maintenance of a constant height. The research by Liu *et al.* (1983) also showed the presence of characteristic intervals of displacement changes in function of the number of applied cycles, but the researchers performed only 10 000 cycles.

The first stage consists of the first 10 000 loading cycles, and is characterized by similar dynamics in both test groups. At the same time, we can see that the decrease in changes of the IVD height (Δh) is significantly greater in the injured segments (AIS) than in the intact segments (IS). After 10 000 cycles, there was a 47% difference in the height decrease Δh between IS and AIS.

In the second stage, the segment height stabilises in both groups and stays at the same level until the end of the test. The average value of Δh amounts to $(4.49 \pm 0.14) \cdot 10^{-2}$ mm in the case of the IS segment and $(9.02 \pm 0.22) \cdot 10^{-2}$ mm in the case of AIS. Also, in the case of loading with a force of 650 N, the global difference between the initial and the final displacement amounts to 2.48 mm for IS and 2.87 mm for AIS. The relative change in the IVD height determined as the difference between the initial and final value changes of the IVD displacement at maximum load amounts to 2.48 ± 0.47 mm in the case of the IS segment and 2.87 ± 0.38 mm in the case of AIS.

The stiffness coefficient k of the tested segments increases with successive loading cycles. Initially, after 10 000 cycles the value k amounts to 0.76 ± 0.21 kN/mm for IS and 0.81 ± 0.18 kN/mm for AIS. Despite the lack of a significant increase in the displacement at a force of 650 N, in subsequent loading cycles, there is a visible further increase in the stiffness coefficient of the tested segments (Fig. 4b). In the middle of the test (after 50 000 cycles) the value is 10.29 ± 3.78 KN/mm for IS, and is higher by 63% than the value obtained for the AIS segments.

In the final loading stage (in 100 000 cycles), the highest values of the stiffness coefficient are observed in the AIS segments $(121.41 \pm 44.81$ kN/mm), which were 66% higher than the values obtained in the IS segments $(40.93 \pm 23.12$ kN/mm).

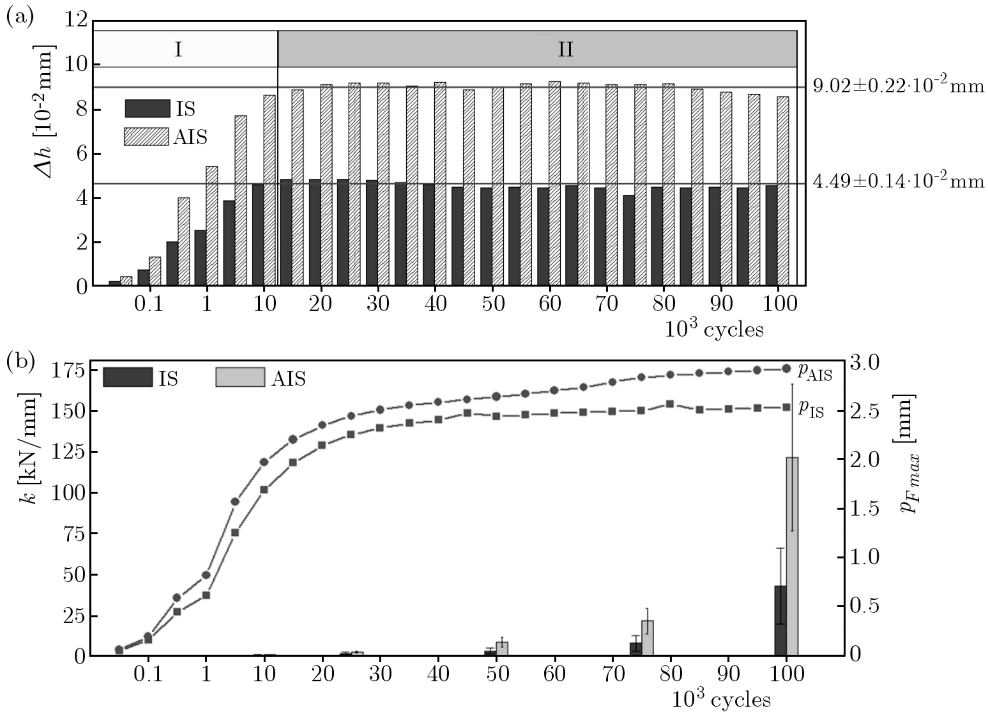

Fig. 4. The characteristics of changes in the mechanical parameters of the tested segments (IS – intact segment and AIS – acutely injured segment) in successive loading cycles: (a) changes of the IVD height (Δh) with marked characteristic stages of decrease in the intervertebral disc height: I – initial dynamic decrease in height, II – maintenance a constant height; (b) the stiffness coefficient (k) at the maximum force, taking into account changes in the displacement at 630-650 N loading

The results confirm that during physiological loading of the intervertebral disc, there is a decrease in height and an increase in stiffness (Johannessen *et al.*, 2004; van der Veen *et al.*, 2007).

Johnnessen *et al.* (2004)examined segments derived from sheep spine and showed that after 10 000 load cycles, the value of the stiffness coefficient falls within the range of 603 to 800 N/mm. It is also the range after which the intervertebral disc can still recover to its previous state by restoring normal hydration.

At the same time, cyclic loading causes changes in the hydrostatic properties of the intervertebral disc, during which there is a change in the direction of the fluid flow in IVD. A loss of water and a drop in IVD height cause simultaneous bulging of the annulus fibrosus (Papadakis *et al.*, 2011). Subsequent loading cycles lead to a further increase in stiffness (despite lack of changes in the intervertebral disc displacement), promoting formation of defects in its structure. On the other hand, Hasegwa *et al.* (1995) indicated that the increase in stiffness, in the range of up to 40 000 cycles of the load, is primarily associated with changes in viscoelastic properties of IVD.

As a result of high compressive loads (about 100 000 cycles), irreversible changes occur in the structure of the annulus fibrosus, as shown in microscopic observation (Fig. 5). Specifically, analysis of sagittal cross-sections of the motion segment showed no degenerative changes within the vertebral body and the end-plate, which often accompany degenerative changes arising with age. Structural studies indicate that one of the signs of degeneration is delamination of the annulus fibrosus (Gregory and Bae, 2012). Because of composite structure of the annulus fibrosus, most of the damage relates primarily to changes within the inner annuli of the disc (Adams *et al.*, 1996; Cassidy *et al.*,1990; Pezowicz *et al.*, 2006a,b) (Fig. 5b). Damage in form of delamination of annulus fibroses lamellae occurred primarily at the posterior intervertebral disc (Fig. 5d), resulting in loss of coherence between the adjacent lamellae. For some of the analysed cross-sections, delamination also occurred in the anterior annulus fibrosus, demonstrated by disorganized distribution of lamellae and clear separation of inner lamellae from the superior end plate (Fig. 5c). Disturbances in the lamellae structure are promoted by migration of the nucleus pulposus, which causes nucleus pulposus herniation. In this study, the dehydration effect and a decrease in the intervertebral disc height cause significant structural changes of the posterior annulus fibrosus. The resulting structural changes destabilize the functions of the intervertebral disc and, consequently, cause transfer of the load-bearing capacity to articular processes (Adams *et al.*, 2010).

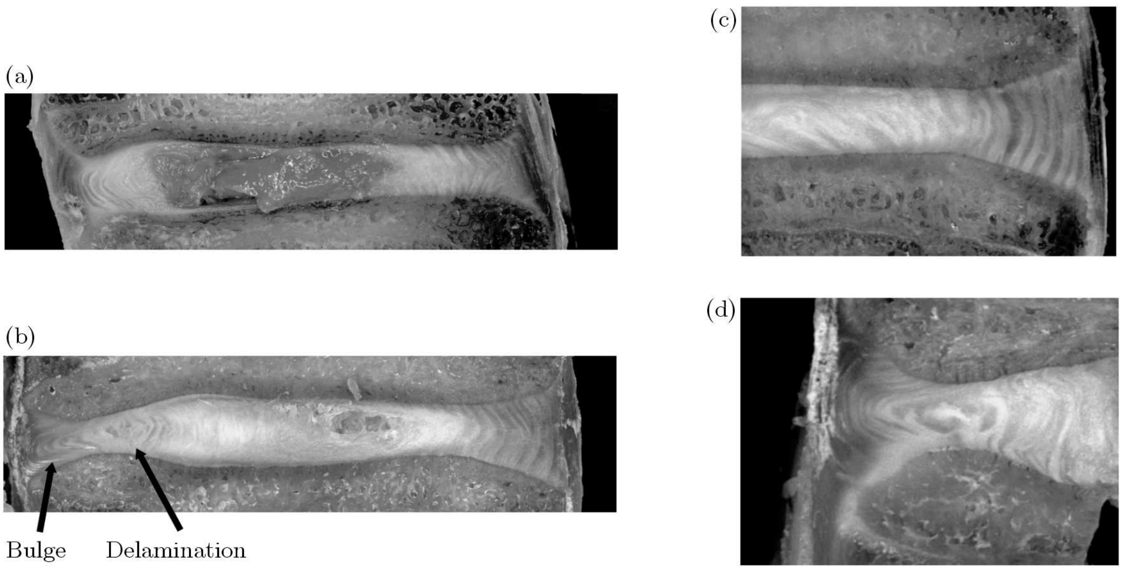

Fig. 5. A sagittal cross-section of the spinal motion segment preserved in glutaraldehyde: (a) unloaded, with clearly visible central nucleus pulposus and an outline of the distribution of annulus fibrous lamellae; (b) after cyclic loading (acutely injured segment), with clearly disturbed annulus fibrosus structure; (c) delamination of inner anterior lamellae of the annulus fibrosus; (d) visible delamination and a clear bulge of posterior lamellae of the annulus fibrosus

The dissipation energy determined for successive loops is a measure of damping effect of the elements included in the motion segment. The initial dissipation energy (ΔE) after 50 conditioning cycles was 23% greater in the case of the IS segments (24.22 ± 12.82 J) compared to the energy obtained for AIS (18.68 ± 4.73 J). At the same time, the energy in the first loading stage (to 10 000 cycles) decreases linearly to 21.15 ± 9.02 J in the case of the IS segments and to 14.56 ± 4.83 J in the case of the AIS segments. In the second stage, the energy changes of the tested segments are characterised by an unchanging course. In the range of 15 000-100 000 cycles, the difference between IS and AIS amounted to 33%. After the completion of the loading cycles, the smallest dissipation energy loss was recorded for the AIS segments, where the energy did not exceed 13.50 ± 6.35 J and was lower by 36% than in the case of the IS segments – Fig. 6a.

After 50 conditioning cycles, the viscoelastic factor (VEF) was higher by 19% in the case of the IS segments ($VEF = 0.15 \pm 0.06$) than in the case of the AIS segments ($VEF = 0.12 \pm 0.01$). The initial VEF value at the first loading stage (to 1000 cycles) decreased linearly. The overall decline in VEF during the tests was 11% for the IS segments and 13% for the AIS segments – Fig. 6b.

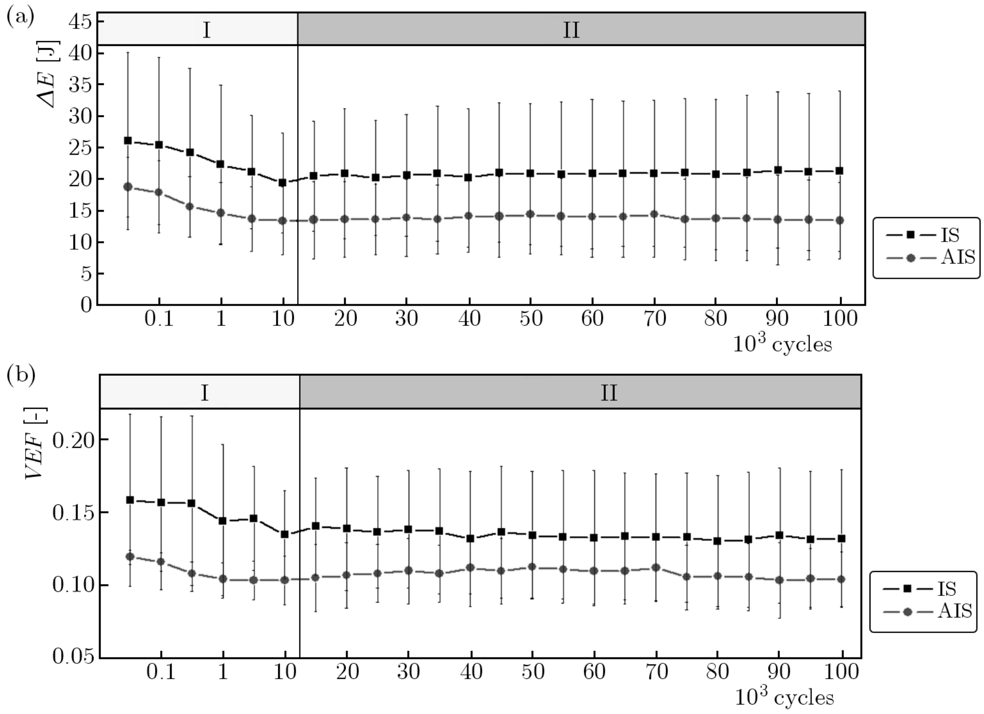

Fig. 6. The characteristics of changes in the viscoelastic parameters of the segments (IS – intact segment and AIS – acutely injured segment) in successive loading cycles with marked distinctive stages of changes in: (a) dissipation energy (ΔE), (b) viscoelastic factor (VEF)

The nonlinear mechanical properties of IVD result from the complex structure of the tissue (Panjabi *et al.*, 1994; Kaigle *et al.*, 1997; Gregory and Bae, 2012; Gohari *et al.*, 2013; Kobielarz and Jankowski, 2013) and are largely related to the loss of water and tissue dehydration (Koeller *et al.*, 1984; Adams and Dolan, 2012). The characteristics of viscoelastic properties of the intervertebral disc change with loading applied to the motion segment, as shown by the results obtained for ΔE and VEF. However, the similar course of the ΔE and VEF curves over time does not give a clear answer to the question on material characteristics of the disc. Therefore, the usefulness of the viscoelastic factor (VEF) proposed by Koeller *et al.* (1984) in assessing the viscoelastic characteristics seems to be negligible.

4. Conclusions

The results of the conducted research show a significant effect of the segment support on mechanical properties of the intervertebral disc in long-term compression testing. As a consequence of damage to the posterior columns (articular processes), there are greater changes in the mechanical properties of the injured segments compared to the intact segments, including a 50% greater drop in IVD height, an increase in the stiffness coefficient at a constant displacement rate, and a clear delamination and deformation of the annulus fibrosus. In the segments with no additional point of support in form of articular processes, the load-bearing function is taken over in its entirety by the intervertebral disc. This also involves an increased range of motion within the segment as the primary role of the articular processes is to stabilize the spine and eliminate its axial rotation during flexion and extension (Adams, 2004).

In assessing the mechanical parameters presented in this work, we should bear in mind that this is not a description of the properties of the intervertebral disc alone, but also of the elements working with it, such as hyaline cartilage or ligaments, and in the case of a full motion segment, we should also take into account the articular processes.

In addition, because of the dominant role of the intervertebral disc in the load-bearing system of the spine, it is important to search for data that would describe the mechanical action of the structure. This is particularly important due to, among other reasons, the increasing percentage of degenerative intervertebral disc diseases among young people, to whom the use of standard stabilization of the spine by fusion does not allow for full return to active life. Alternatively, disc prostheses can be used, which copy the mobility characteristics of a natural disc but in most cases do not provide adequate flexibility to reflect the amortisation and load-bearing functions in a manner similar to physiological processes.

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