FINITE ELEMENT ANALYSIS OF WEIGHTBATH HYDROTRACTION TREATMENT IN THE CASE OF OSTEOPOROSIS

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Abstract

3D finite element analysis of the first elastic period of the weightbath hydrotraction treatment is presented to analyze the effect of osteoporosis during the traction procedure. A systematic parameter analysis of the material moduli of the aging spinal motion segment with osteoporotic bone was investigated. It was concluded that the osteoporosis in itself can not be a contraindicating factor of weightbath hydrotraction treatment. However, if applying extra weigts, beside the quality of bone and the grade of osteoporosis, the age of patients, their body structure and body weight must be carefully considered as well.

Keywords: weightbath hydrotraction treatment, lumbar spinal motion segment, indirect and direct traction, elongation of disc, osteoporosis

Introduction

A large percent of population is affected by low back pain, starting from the degeneration of lumbar spinal structures. In some cases, traction might be the effective treatment. Weightbath hydrotraction therapy (WHT) is a method of hydro- or balneotherapy where the patient is suspended in water, loaded by extra weights applied on certain points of the body, to stretch the different parts of the spinal column or lower limbs. The weightbath hydrotraction method, its indications, contraindications, and clinical effects, its application, equipment and the biomechanics of it were detailed in.[1] However, the question has not been answered yet that what is the relation between WHT and osteoporosis, or rather, is it possible to apply the treatment for strongly osteoporotic patients?

In this study a systematic parameter-analysis is used for the analysis of the mutual effect of the different material moduli of the components of the lumbar motion segment and the vertebral cancellous bone during the special loading conditions of the traction under the water.

Although finite element (FE) simulations are increasingly applied to examine the mechanical behaviour of healthy or degenerated spine or the effects of surgical treatments; as far as authors know, FE analyses of the weightbath-like underwater traction treatment can not be found in the literature except for[2] where 3D finite element models (FEM) of human lumbar functional spinal units (FSU) were used for the numerical analysis of weightbath hydrotraction therapy (WHT) in the case of healthy and degenerated lumbar spine. In this study the FE model developed in[2] has been extended to the analysis of WHT applied for osteoporotic lumbar spine.

Methods

For the numerical analysis of the effect of WHT on osteoporotic spine, the FEM model that we developed earlier in ANSYS system[2] was used, representing five degeneration grade of aging. A 3D model of a typical lumbar segment L4-5 was created[3-4] by using Pro/Engineer code. Cortical and cancellous bone of vertebrae was separately modeled, including posterior bony elements and facet joints. The height of the disc was considered to decrease linearly from 10 to 6 mm for the five aging degeneration degrees. The endplates were divided into external bony and central cartilaginous part. Accordingly, the annulus matrix was divided into internal and external ring and three layers of annulus fibers. The FE mesh was generated by ANSYS Workbench and the connections between the several geometrical components were integrated to the FE model by ANSYS Classic. The FE model consisted of solid, shell and bar elements. Annulus matrix, nucleus, cancellous bone, articular joints and different types of attachments were modeled by solid elements; cortical shells and endplates were modeled by shell elements. The compatibility between the adjacent solid and shell elements was guaranteed by contact elements. All ligaments were modeled by shell elements.

Components of FSU	Young's mod [MPa]	Poisson's ratio
vertebral cortical bone	12000	0.3
posterior elements, facet	3500	0.3
vertebral cancellous bone	150	0.3
bony endplate	12000	0.3
cartilaginous endplate	100	0.4
nucleus	1	0.499
annulus ground substance, internal	4	0.45
annulus ground substance, external	5	0.40
annulus fibers	500/400/300*	-
anterior longitudinal ligament	8**	0.35
posterior longitudinal ligament	10**	0.35
other ligaments	5**	0.35

*external/middle/internal fibers, **tension only

Table 1. Material moduli of the components of healthy motion segment

Table 1 shows the material moduli of healthy lumbar motion segment. For the bony elements and endplates, for both tension and compression, linear elastic isotropic materials were applied, based on the literature. Annulus ground substance and nucleus were considered linear elastic for compression and bilinear elastic for tension. Nucleus and annulus matrix were considered linear elastic. Collagen fibers of the annulus were considered as bilinear elastic isotropic tension-only material. All the seven ligaments were integrated in the model with bilinear elastic tension-only materials of the literature again.

Five grades of age-related degeneration process were introduced, seen in *Table 2* separately for compression and tension. Age-related normal degeneration processes of segment start generally in the nucleus. A healthy young nucleus is in hydrostatic compression state. During aging, the nucleus loses its incompressibility by changing gradually from fluid-like to solid material of increasing stiffness. These kinds of nucleus changes were modeled by decreasing Poisson's ratio with increasing Young's modulus, seen in *Table 2*. This behavior is generally accompanied by the stiffening process of the annulus. This procedure was modeled also by increasing Young's modulus with slightly decreasing Poisson's ratio, by distinguishing the internal capsular and the external ligamentous part of annulus, by considering the internal annulus to be weaker. The elastic moduli of annulus fibers were decreased during aging.

Grades of aging degeneration* (Young's mod/Poisson's ratio)	**grade 1** (healthy)	**grade 2**	**grade 3**	**grade 4**	**grade 5** (fully deg.)
disc height [mm]	10	9	8	7	6
For compression					
nucleus	1/0.499	2/0.475	6/0.45	16/0.425	36/0.4
annulus matrix, internal ring	4/0.45	4.5/0.44	6.5/0.43	11.5/0.42	20/0.41
annulus matrix, external ring	5/0.40	6/0.39	9/0.38	17/0.37	29/0.36
cancellous bone	150/0.3	125/0.3	100/0.3	75/0.3	50/0.3
cartilaginous endplate	100/0.4	80/0.4	60/0.4	40/0.4	20/0.4
annulus fibers (ext/middle/int)	500/400/300	250/200/150	125/100/75	63/50/38	10/10/10
For tension					
nucleus	0.4/0.499	1/0.475	1.6/0.45	2.2/0.425	2.8/0.4
annulus matrix, internal ring	0.4/0.45	1/0.44	1.6/0.43	2.2/0.42	2.8/0.41
annulus matrix, external ring	0.5/0.40	1.2/0.39	2/0.38	3/0.37	3.5/0.36
anterior longitudinal ligaments	8/0.45	5/0.45	3/0.45	2/0.45	1/0.45
posterior longitudinal ligaments	10/0.45	6.5/0.45	4/0.45	2/0.45	1/0.45
other ligaments	5/0.45	5/0.45	3/0.45	2/0.45	1/0.45

*Other elements are seen in *Table 1*

Table 2. Modeling of age-related degeneration for compression and tension

For the annulus ground substance and for the nucleus were considered linear elastic material in compression, and bilinear elastic in traction. In the indirect phase of traction the compressive material moduli, in the direct phase of traction tensile Young's moduli of annulus matrix and nucleus were used, seen in *Table 2*. The compressive moduli were applied from the literature, the tensile moduli were determined by parameter identification based on the in vivo experiments made in traction bath.[9-10] For healthy nucleus we supposed fluid-like incompressible material both for tension and compression. For the nucleus fibers and spinal ligaments we supposed that during aging the fibers and ligaments elasticity decreases, that is, they are in more and more elongated state, instead of a gradual stiffening with a more rigid behaviour.

The traction forces occurring along the spine during WHT are detailed in.[1] During WHT, in the different parts of the spinal column different tensile forces may occur, depending (1) on the relative density of the human body and the water, (2) on the value and position of the applied extra weight loads, and first of all, (3) depending on the mode of suspension.

The classification of traction loads is based on the definition of traction elongation of segments. Since nobody knows the intact load- and deformationless state of segments and discs, a reference state must be chosen. In this way, elongation of segments is specified as an extension compared with the state of segments just before the traction bath treatment in normal upright standing position. That is, zero elongation belongs to the compressed reference state of segments just before the treatment.

The traction loads are related to the same reference state, according to which there are two components of traction loads: (1) the indirect traction load, namely, the decompressive force consisting of the removal of the compressive preload of body weight and the removal of muscle forces that are partly or totally relaxed during the treatment; and (2) the direct traction load consisting of the active tensile force due to the buoyancy and the applied extra loads reduced by the buoyancy, as well. Consequently, the traction process in itself can also be divided into an indirect and a direct phase.

We applied exclusively cervical suspension in the water. In this case at the lumbar level the decompressive force is the weight of the upper body, that is about 58-60 % of the body weight,[5] completed by the muscle forces that are approximately the same as the upper body weight,[6-7] since the muscles are completely relaxed in water. Thus, the indirect traction load yields $F_1 = 2 \cdot 0.6 \cdot G = 1.2G$. The direct tensile force from the body weight and the extra load depend on the buoyancy,[8] namely, on the density ρ_b of the human body, ρ_w of the water and ρ_l of the lead material of extra loads. This way the direct tensile load from the body weight at the lumbar level is $0.42G(1-\rho_w/\rho_b) = 0.016G$ if $\rho_b = 1040\,kg/m^3$ and $\rho_w = 1000\,kg/m^3$. This load is surprisingly small, so the idea of applying extra weights seems to be evident. The extra load from lead weights W yields $W(1-\rho_w/\rho_l) = 0.912W$ if $\rho_l = 11350\,kg/m^3$. Thus, finally the direct traction load yields $F_2 = 0.016G + 0.912W$. By supposing $G = 700N$ body weight and $W = 2 \cdot 20 = 40N$ extra loads, the indirect and direct traction loads yield 840 N and 47.7 N, respectively.

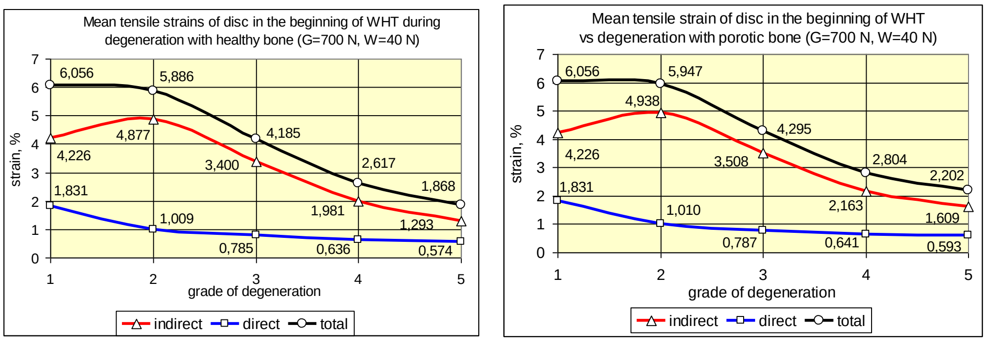
For the numerical simulation of WHT we applied a normal body weight of 700 N and 3x20 N extra lead weights applied on the ankles, thus the standard load were 850 N indirect and 50 N direct traction forces. The load was distributed along the superior and inferior surface of the upper and lower vertebra of the segment, by applying rigid load distributor plates on the surfaces. This load was acting during the 20 minutes long duration of the treatment.

WHT is a typical viscoelastic process with initial instant elastic and 20 minutes long creeping phases. Thus, the elongations can be divided to initial elastic and following creeping parts. In this study we analyze the osteoporotic relations in the initial elastic part of the treatment only. The creeping part depends on the damping characteristics of the components of the motion segment that was measured during the WHT treatment of patients by.[11]

In this study we assumed that all components of the motion segment are under normal degeneration according to the data of *Table 2* except for the cancellous bone and the endplate that remained intact with the data of grade 1. Then the elastic modulus of cancellous bone and the cartilaginous endplate was separately and simultaneously gradually decreased as seen in *Table 2* in which osteoporotic weakening was modeled. In the analysis the material moduli of the cortical bone were kept changeless. Then the obtained results, elongations and stresses in the components of disc and the disc contractions were compared.

Results

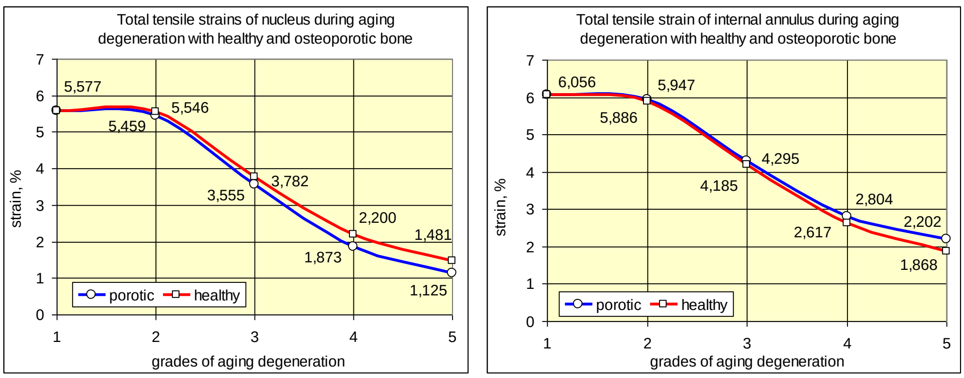
In the following the results are related to the instant beginning period of WHT, during which the behaviour of nucleus and annulus is bilinear elastic, namely, first the indirect load acts due to the remove of the upper body weight with the muscle forces, just after the direct traction load starts to act due to the buoyancy from the body and extra loads under the water.



a) b)

Figure 1. Mean indirect (from 850), direct (from 50N) and total (from 850+50N) tensile strains of the disc in the beginning of WHT for the grades of age-related degeneration process of lumbar motion segment with healthy (a) and osteoporotic (b) vertebral cancellous bone

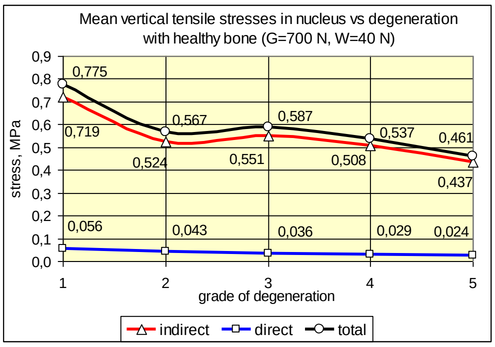
Figure 1 illustrates the mean tensile strains of intervertebral disc from the indirect (850N), direct (50N) and total (850+50N) traction load the disc for a patient of 700N body weight with 2x20 N extra lead weight on the ankles in the grades of age-related degeneration process of segment with healthy (*Figure 1a*) and osteoporotic (*Figure 1b*) vertebral cancellous bone. Compared to the healthy case, the mean total strains of disc in osteoporotic case increased slightly, by 1, 3, 7 and 18% in grade 2, 3, 4 and 5 respectively.



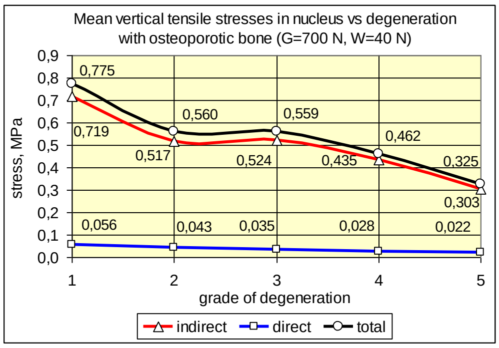
a) b)

Figure 2. Total tensile strains (from 850+50N) of the disc nucleus (a) and external annulus (b) for a patient of 700N body weight with 2x20 N extra lead weights on ankles with healthy and osteoporotic cancellous bone in the beginning of WHT for the grades of degeneration process

However, the certain parts of the disc showed strongly different elongations and tensile strains, seen in *Figure 2*, where the total (indirect + direct) tensile strains of the disc nucleus and external annulus can be seen. While in the nucleus the tensile strains decreased in osteoporotic case by 2, 6, 15 and 24%, in the external annulus the strains increased by 3, 10, 23 and 45%, for the aging grades 2, 3, 4 and 5, respectively. At the end of the elastic phase of WHT, in the elderly, in grade 3-5, the osteoporotic elongations and strains are 15-25% smaller in the middle of the disc and 25-45% larger in the edge of the disc.



a)



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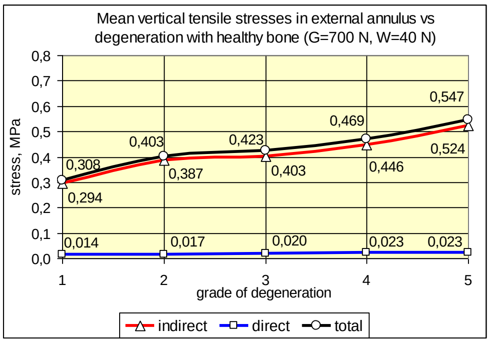
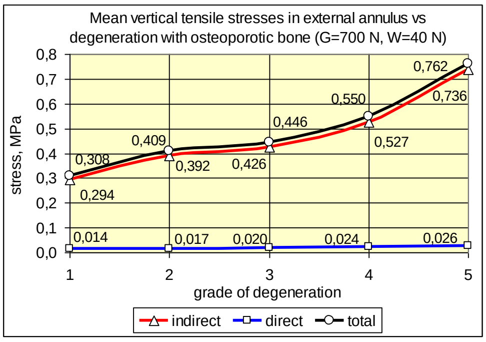


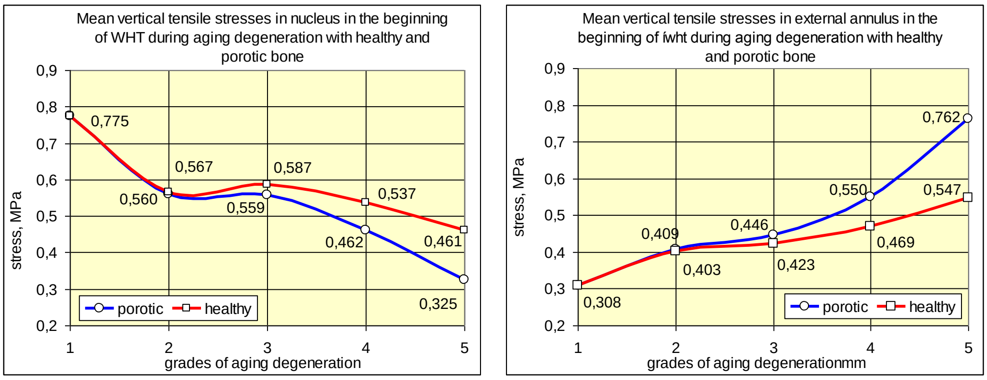
c)



d)

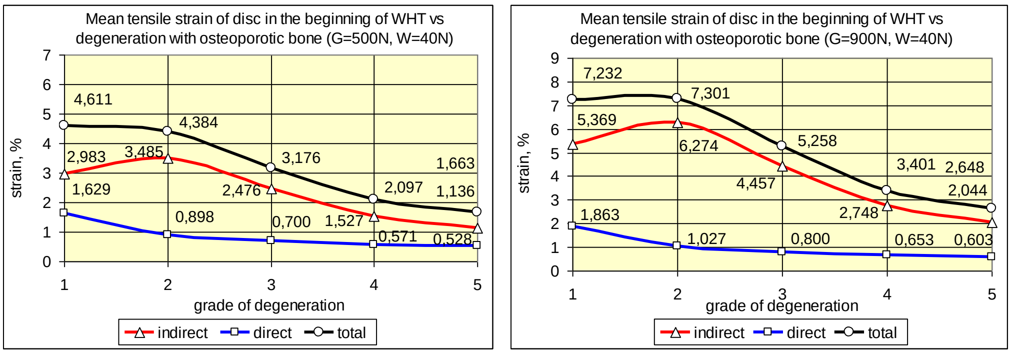
Figure 3. Mean indirect (for 850 N), direct (for 50N) and total (for 850+50N) tensile stresses in the nucleus with a) healthy and b) osteoporotic bone and in the external annulus with c) healthy and d) osteoporotic cancellous bone in the beginning of WHT for the grades of age-related degeneration process of lumbar motion segment

In *Figure 3* the vertical tensile stresses in the nucleus (*Figures 3a, 3b*) and in the external annulus (*Figures 3c, 3d*) are illustrated from the indirect (850N), direct (50N) and total (850+50N) traction load in the grades of age-related degeneration process of segment with healthy (*Figures 3a, 3c*) and osteoporotic (*Figures 3b, 3d*) vertebral cancellous bone. Compared to the healthy bone case, in osteoporotic case the mean total tensile stresses in the nucleus decreased by 1, 5, 14 and 29%, while in the external annulus the stresses increased by 1, 5, 17 and 39% for the aging grades 2, 3, 4 and 5, respectively, as shown separately for the nucleus in *Figure 4a* and for the external annulus in *Figure 4b*. At the end of the elastic phase of WHT, in the elderly, in grade 3-5, the osteoporotic sagittal tensile stresses are 15-30% smaller in nucleus, but 20-40% larger in the external annulus.



a) b)

Fig. 4. Mean total vertical tensile stresses of the disc nucleus (a) and external annulus (b) with healthy and osteoporotic cancellous bone in the beginning of WHT for the grades of age-related degeneration process of lumbar motion segment



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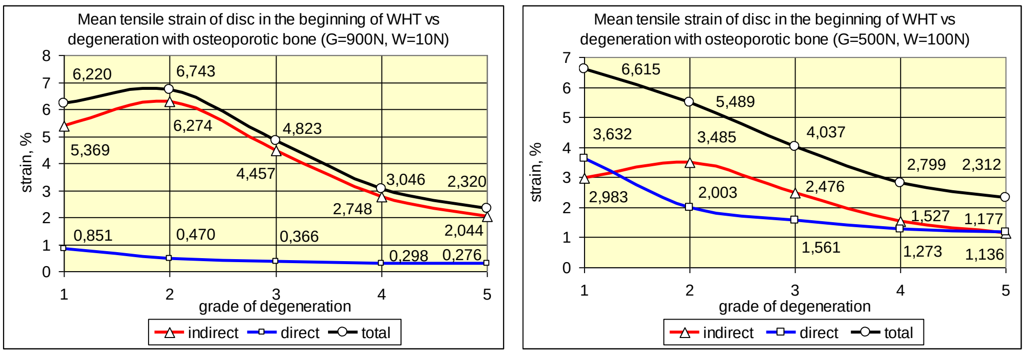
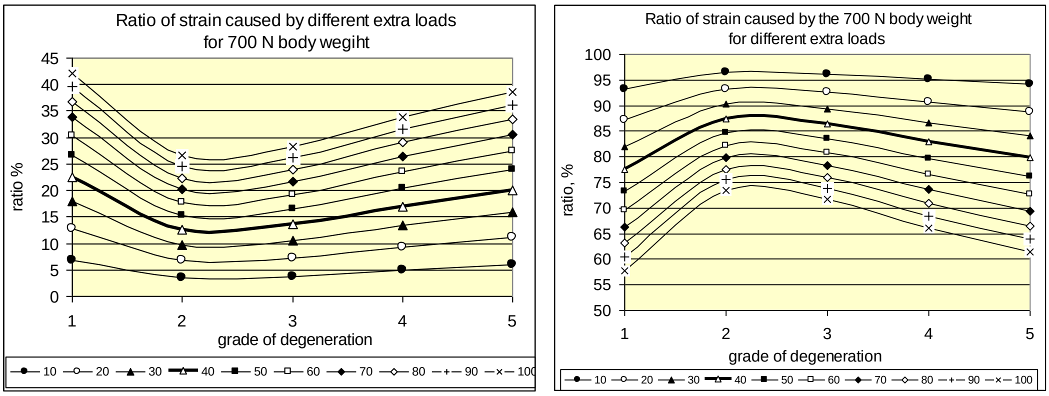


c) d)

Figure 5. Mean indirect (for 850 N), direct (for 50N) and total (for 850+50N) tensile strains of the disc in the beginning of WHT for the grades of age-related degeneration process with osteoporotic cancellous bone, for the cases of different body weights G and applied extra loads W: a) G=500N , W=40N; b) G=900N, W=40N; c) G=900N, W=10N; d) G=500N, W= 100N

In the WHT the extra weight has a very important role in the traction effect. In *Figure 1b* the traction strains of disc were illustrated for the generally applied 2x20N extra weights for a osteoporotic patient of normal 700N body weight. In Figures 5a and 5b the same extra lead weight was applied but for a small thin, and for a large corpulent equally osteoporotic patient of 500N and 900N body weight, respectively. While in the corpulent patient, the ratio of direct traction effect was only 10-18% of the total one, for the thin patient it was 18-30%. *Figures 5c* and *5d* show the extreme cases of the under-loaded (2x5N) corpulent patient with 3-5%, and the overloaded (2x50N) thin patient with 33-50% direct traction effect.

Figure 6 summarizes the traction effect of extra weight loads for osteoporotic patients of normal body weight of 700N. The load was gradually increased by 2x5N load steps to 2x50N load. *Figure 6a* shows the ratio of traction effect caused by the extra loads, *Figure 6b* shows the ratio caused by the body weight. The heavy line among the curves related to the generally applied 2x20N extra weight. It can be seen that the extremum of all curves on both figures was located around the degeneration grade 2 of weakly degenerated young adult age.



a) b)

Figure 6. The traction effect of the extra load for osteoporotic patient with 700N body weight: the ratio of tensile strain caused by the extra weight (a) and caused by the body weight (b) by increasing the extra load from 2x5N to 2x50N, increased proportional by 2x5N increments

Disc contraction is influenced by the external annulus elongation that increases in the case of osteoporosis. Disc contraction of a normal 700N body weight with 2x20N extra weights increased by 5-25% for osteoporotic elderly.

Discussion and conclusion

Based on the numerical analysis, we can state that the load bearing zone in the disc moves from inside to outside. In the case of healthy trabecular bone the support of the nucleus both in tension and compression is strong, thus, in traction, higher central deformations occur. As the resistance of the bone decreases due to osteoporosis mainly in the middle domain of vertebrae, the deformations of the nucleus decrease and that of the external annulus increase. For healthy trabecular bone the middle of the disc showes the higher elongations, for osteoporotic bone the external regions give the larger elongations.

In agreement with earlier results of spinal degeneration analyses[2,12] the age-related deformability is maximum in the young adults in grade 2, as seen in the case of traction bath treatment as well (*Figure 1*). This yields that the traction effect of the extra loads is also minimum around grade 2, for weakly degenerated young adults (*Figure 6a*), in line with the maximum traction effect of body weight in the same age (*Figure 6b*).

By taking into account that the in vivo measured elongations in WHT for osteoporotic elderly over 60 years with 2x20N extra load was in the elastic phase of WHT about 0,23 mm that increased during the 20 minutes long viscoelastic phase of the trealment to about 0,55 mm detailed in,[9-11] we can conclude that the osteoporosis in itself can not contraindicate the weightbath hydrotraction treatment. This result is supported by the present numerical analysis, as well. However, if applying extra weigts, beside the quality of bone, the grade of osteoporosis, the body structure and body weigt, together with the age of patiens must be carefully analyzed, by means of the result seen above.

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