Neuroendocrinology Letters Volume 37 No. 4 2016
ISSN: 0172-780X; ISSN-L: 0172-780X; Electronic/Online ISSN: 2354-4716
Web of Knowledge / Web of Science: Neuroendocrinol Lett
Pub Med / Medline: Neuro Endocrinol Lett

Evaluation of rheological parameters of the axial system using the Transfer Vibration through Spine (TVS) method

Šárka Panská [1], Tereza Píglová [1], Josef Zeman [2], František Maršík [3,4], František Lopot [1], Karel Jelen [1]

1 Faculty of Physical Education and Sport, Department of Anatomy and Biomechanics, Lab. of Biomechanics of Extreme Loading, Charles University, Czech Republic
2 Faculty of Engineering, Czech University of Life Sciences, Czech Republic
3 Institute of Thermomechanics of Academy of Sciences, Czech Republic
4 Faculty of Mathematics and Physics, Charles University,Czech Republic

Correspondence to: Šárka Panská, MSc.
Department of Anatomy and Biomechanics,
Lab. of Biomechanics of Extreme Loading, Charles University of Prague
José Martího 31, 162 52 Prague 6, Czech Republic.
TEL: +420 220 172 353; E-MAIL: spanska@ftvs.cuni.cz

Submitted: 2016-07-01 *Accepted: 2016-08-28* *Published online: 2016-09-30*

Key words: **TVS method; axial system; mechanical loading; rhythmic gymnastics**

Neuroendocrinol Lett 2016; **37**(4):301–307 **PMID:** 27857047 NEL370416A05

Abstract

OBJECTIVE: The human motion system reacts to both hypo and hyperactivity loads by changes to the rheological properties of tissues. This study deals with changes to the axial system (AS) compartment. Using the appropriate methodologies and mathematical-physical methods, these changes can be identified and quantified.
METHODS: This study describes the noninvasive TVS (Transfer Vibration through Spine) method, which was applied to assess the AS selected mechanical properties in various modes. A pilot study was conducted on a top-level twelve-year-old girl-gymnast. The data detection was carried out in three cycles, before and after a peak 3.5 hour training session and the next day, after resting, just before the next training.
RESULTS: Specifically, the values of selected rheological parameters, the AS damping coefficient b and viscosity μ, were obtained. The dynamics of their changes, in the stated load cycles, has also been shown. The damping coefficient b fell from the value of 0.626 to 0.324 before training and increased to 0.394 after resting. The viscosity coefficient μ showed a similar trend, namely falling from the value of 9.85 [Pa.s] to 2.15 [Pa.s] and then increasing to 3.8 [Pa.s] .
CONCLUSIONS: With its computational solution, the TVS method,is a diagnostic apparatus making it possible to classify AS properties, both quantitatively and qualitatively, or its chosen segments and their changes, respectively. It can be used in classifying, preventing and treating the consequences of extreme motion and relaxing modes. The TVS application also makes it possible to control AS states over therapeutic, recovery, ergonomic and other loading modes of the human locomotion system.

ORIGINAL ARTICLE

INTRODUCTION

Vertebrogenic disorders are a common health problem, which can be seen in populations spanning all age groups. These problems can be caused by many factors. They may be problems caused due to the lack of physical activity – hypokinesia, or vice versa due to overloading – hyperkinesia (Jelen *et al.* 2013) connected e.g. with unhealthy lifestyles, obesity, improper nutritional regimes, and other factors, including genetic ones (Panská *et al.* 2013) negatively acting on all the organ systems including the axial system (AS).

A number of changes in the rheological properties of biological components of AS occur in the course of a lifetime due to ageing and load bearing. An example of this is degeneration of intervertebral discs (IVD), which has a significantly higher prevalence of degeneration in comparison with the musculoskeletal tissue.

Such issues manifest themselves by reducing the nucleus pulposus gelled form, changes to the disc morphology and frequent irregularities of the annuli fibrosi lamellae and disorganization of the collagen and elastin networks, an ingrowth of blood vessels and nerves to fissures or the incidence of necrotic (50% in adults) or apoptotic cells, biochemical changes, etc. (Urban & Roberts 2003).

The loss of proteoglycan in the degenerated intervertebral plate (Lyons *et al.* 1981) has a great influence on its behavior under load. With the loss of proteoglycan, reducing the osmotic pressure in IVD (Urban & McMullin 1988) it is less capable of maintaining hydration in the load. Less water is contained in degenerate IVD than a healthy plate (Lyons *et al.* 1981) and thus the load loses its height, respectively volume (Frobin *et al.* 2001) and the fluid quickly. The discs subsequently have a tendency to prolapse.

Proteoglycan loss and degradation of the matrix also have other important effects on the mechanical properties, because, due the subsequent loss of hydration, the degenerated IVD no longer behaves as a highly viscous, almost incompressible tissue when loaded (Adams, McNally & Dolan 1996). The loading could then lead to inappropriate stress accumulation along the pressure plates – the end plates, or in the fibrous ring. The load concentration, observed in the degenerated IVD, has also been associated with pain resulting from IVD changes (McNally *et al.* 1996).

Changes to the IVD behavior have a strong influence on other spinal structures and can influence their function and susceptibility to damage. For example, due to altitude rapid loss of the IVD degenerated at loading, the apophyseal joints, adjacent to these discs, may suffer from abnormal loads (Adams *et al.* 1990), and finally osteoarthritis changes may develop at these sites. IVD height loss can affect other structures. For example, these changes reduce ligamentum flavum voltage power, and hence they may cause a change in structure and consequent thinning. With subsequent loss of elasticity (Postacchini *et al.* 1994), the ligament will tend to bulge into the spinal canal, resulting in spinal stenosis – a problem which increasingly appears not only in the ageing population.

A domain, in which we can certainly meet hyperkinetic loading, is the field of sports training. Top level sporting performance is often reached through specific monotonous or one-sided loading, affecting human organism more commonly from early childhood, and furthermore, often with an insufficiently designed compensational and regenerative regime. Acute macrotraumas, overuse, injuries linked to repetitive microtraumas aren´t sporadic events, quite to the contrary(Kerssemakers et. al., 2009).

We consequently can encounter premature detritions and degeneration (wear and tear) of tissues and structures of spine, for example: the degeneration, herniation and height reduction of intervertebral discs, the deterioration of vertebral apophyses, spondylolysis, spondylolhistesis etc. As a result of on-going degenerative changes and hypo-/hyper- kinetic loads, the organism continuously reacts, for example by neuromotor responses, which may lead up to e.g. muscle contractures and facet joint blocks (spinal motion segments). Evenvertebrae position misalignments may arise which are also affected by trunk muscles recruitment patterns and a prestress in the passive structures (ligaments, facet joints and other structures including intervertebral discs). Furthermore, the position of the vertebrae is affected by the spine profile, body weight and its distribution, ageing and the extent of degeneration (Zander *et al.* 2016).

Changes to the mechanical conditions of the spine manifest different activators and co-contraction patterns of muscle recruitment. E.g., an increased activation of the muscles, also in the resting position of the spine, serves to prevent excessive movements within the motion segment and thus provoke pain. Or, e.g., the substitution of the upper body part support during trunk flexion through active muscle power instead of stretching the elastic forces posterior annulata, ligaments and muscles along the spine (van Dieen *et al.* 2003). The vertebral body height, disc height, processi transversi width and spinal curvature belong to the most important variables affecting the spine muscular-skeletal load (Putzer *et al.* 2016).

In our methodological study, we will track the changes in the rheological properties of AS biological components as a result of various stress modes. The area of our study focused on the peak of rhythmic gymnastics (RG), where the emphasis is placed on performance owing to a high degree of flexibility of joints in the lower extremities and the entire AS. The impact load caused by the use of large amounts of hops and big jumps is also high, leading to a positive effect on bone metabolism (Helge & Kanstrup 2002; Tournis *et al.* 2010), however these can also negatively influence (a lot of rebounds and impacts) the AS damping abilities.

Due to an excessive degree of using motion shapes which are joint flexibility-intensive, the AS is the most stressed part of body gymnastics. Although RGranks among sports with a low injury rate (Cupisti *et al.* 2007), its common asymmetric load is very problematic, leading on occasion to muscle imbalances but also to irreversible morphological changes (Hutchinson 1999), as well as causing chronic damage (Papavasiliou *et al.* 2014; Tanchev *et al.* 2000). For extreme loads combined with biological, biochemical and mechanical factors, along with possible injuries, the acceleration of interior-articular pathologies starts, where the prevalence of osteoarthritis in peripheral joints and spine is significantly higher than in the normal population (Gouttebarge *et al.* 2014).

From the above-mentioned facts we can logically deduce a need to identify changes to the AS mechanical properties. For their qualification and quantification it is necessary to use specific detection and mathematical methods which are capable of identifying the onset of vertebrogenic problems early. With their help we can also optimize preventive, training, compensation and regeneration approaches not only in the RG, but also in other sports or working modes, as well as convalescent modes, e.g. following operations.

We will show that the changes of IVD material properties, or the AS entire complex, respectively, can be indicated with some accuracy by analyzing the transmission of spine mechanical waves using the method of Vibration Transfer through Spine -TVS (Figure 1).

METHODS

The newly elaborated method of the *Transfer Vibration through Spine* (*TVS)* issues from the publications: (Jelen *et al.* 2010; Machač 2011; Maršík & Dvořák 1998; Maršík *et al.* 2010). It is based on the ability of materials to transmit force pulsations, which propagate through tissue pressure pulsations. Pressure pulsations generate in the tissue corresponding density variations of mechanical energy. This mechanical energy is transmitted to tissues, and due to their viscoelastic properties, is partially absorbed (elastic deformation) and partially dampened due to the viscosity. The transmission speed wave (force pulse) and change in amplitude (its drop) is associated with the tissue parameters which are relevant for the transmission of mechanical energy, i.e. elastic modulus, viscosity and plasticity, respectively.

Several studies have been conducted in which the detection of the vibrational excitation transfer to the axis system were made using the TVS method for drivers before and after driving a car. The same measurement of changes in the transmission of AS mechanical waves was also performed with a pregnant female driver at different stages of her pregnancy (Jelen *et al.* 2012).

In our case report, we have presented our TVS method (just in process of completion) when analyzing one top junior girl-gymnast (12 years). Her load

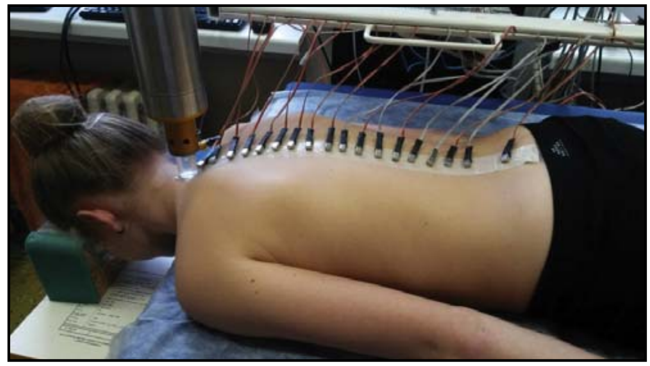

Fig. 1. Oscillation transmission in the axial system (AS) detected using the method of TVS -Transfer Vibration through Spine.

mode is a standard training of 18–20 hours per week. To introduce the principle and functionality of the TVS methods, we chose the gymnast 24-hour daily schedule. The data detection took place in three phases. Before training load, immediately after the 3.5-hour training session and the following day before the next training load. When analyzing, the data started from a detecting the AS response to the excitation signal. At the dorsal – ventral side vertebrae (spinal promontories Th_1–Th_4), the one-component acceleration size in response to a driving signal to C_7 (Figure 2) was detected.

From Figure 2 it is clear that AS can be viewed as an assembly of rigid segments representing the vertebral bodies, IVD viscoelastic segments and the muscle ligaments, encircling its own skeletal system. There issues, from this viewpoint, also a design of methods for evaluating the AS response to the selected excitation signal.

The result reveals the amplitude waveforms of the vertebrae monitored at appropriate frequencies. To prevent adaptive changes due to neuromotoric responses of the organism to the spine mechanical conditions (van Dieen *et al.* 2003), an excitation of the periodically increasing and decreasing frequencies, from 5 to 180 Hz and vice versa, is applied. The entire recording cycle lasts 3 × 3 minutes, i.e., three pairs of increasing and decreasing excitation frequencies are recorded. Schematically, the AS response to the driving signal is shown in Figure 2.

A. The first method provides contracting attenuation values of the excitation signal as

$$y = a\, e^{-bx} \quad (1)$$

where:
a – amplitude
b – damping coefficient
x – vertebra coordinate

The relationship stated describes the decline pattern expected in the wave amplitude, which spreads in the AS from the site of excitation. To evaluate the response of the AS to the selected excitation signal the variable

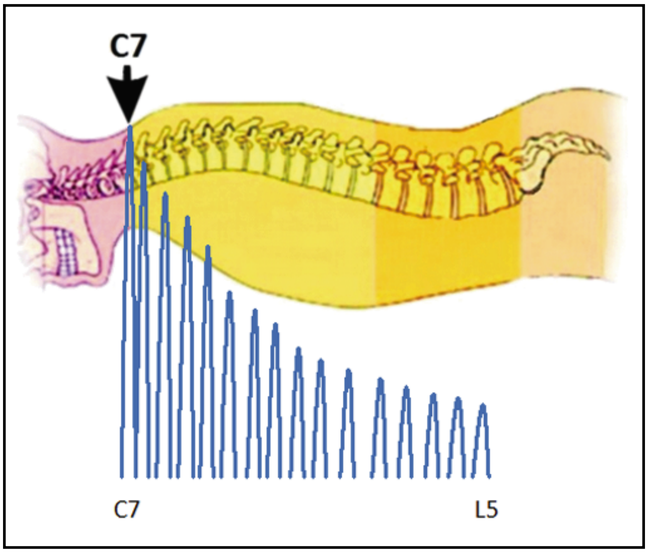

Fig. 2. Schematic representation of the individual vertebrae responses with the AS shock absorbing effect on the excitation signal to C_7.

***b** –damping coefficient is used*. This is marked as a contractual one due to disregarding the real dimensions of the spine measured, when the data of individual vertebrae are in the charts, from which the quantity stated is subtracted, arranged according to their order of 1 (e.g.) to 18 (see Figure 2).

This more heuristic approach shows the AS viscoelastic properties, however the parameters *a,b* have no appropriate interpretation of the material parameters of the examined tissue.

B. The second method is based on an analysis of adjacent vertebrae oscillation, which occurs in the AS resonance to the standing waves. The objective is to determine the viscoelastic properties of an environment for the character oscillation responsible, therefore IVD. This method ensures the evaluation of the AS response to a selected excitation signal the dynamic viscosity, i.e., a variable with a clear physical interpretation. Even in this case it deals with a contract parameter, where, for the simplicity of calculation, we consider the same height of the vertebrae, $l_1 = l_2 = l_3 = l_4$. The stated parameter $\boldsymbol{\mu}$, which has physical dimension viscosity [Pa.s] is defined as:

$$\mu_2 = -\frac{2\rho\omega_r\left(l_2+l_3\right)^3}{\left(2\pi\right)^3 l_2}\ln\frac{a_2}{a_1},\quad \mu_3 = -\frac{2\rho\omega_r\left(l_3+l_4\right)^3}{\left(2\pi\right)^3\left(l_2+l_3\right)}\ln\frac{a_3}{a_1} \quad (2)$$

where:

μ_2 – tissue viscosity between section C_7 and Th_2, it can be assumed that this expresses the IVD viscous properties between vertebrae Th_1, Th_2 [Pa.s]

μ_3 – tissue viscosity between section C_7–Th_3 expresses the IVD viscosity between vertebrae Th_1,Th_2, Th_2, Th_3 [Pa.s] etc.

π – constant

ρ – density 1000 [kg.m^{-3}]

ω_r – resonance frequency [s^{-1}]

a_i– acceleration [m.s^{-2}], i=1,2,3,...

$l_{1,2,3}$, – vertebral heights [m]

The idea of the chosen AS model described above is outlined in Figure 3.

EVALUATION OF THE EXPERIMENT

A. Detection of damping characteristics

Considering the equation (1), we assume that the AS acts as an environment which dampens passing waves. The decrease in amplitude with increasing distance from the driving point assumes an exponential character. The exponential shape – thus the AS response –

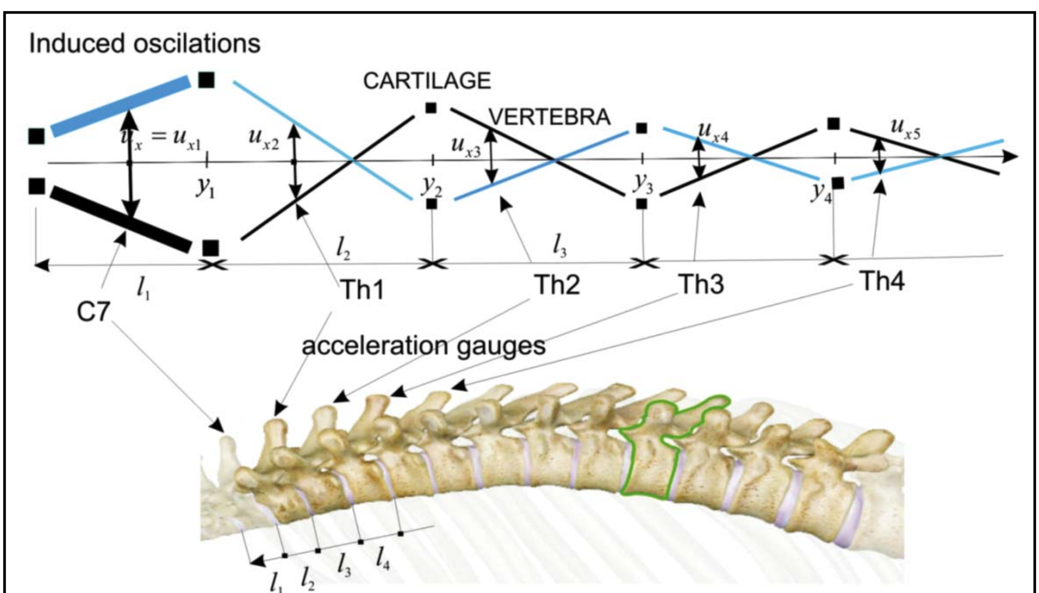

Fig. 3. Geometric scheme of the oscillating AS components and their parameterization. u_x – deflection of the oscillating motion segment [m]; y_i – vertebrae coordinates [m]; $l_{1,2,3}$ – vertebral heights [m]; C_7, Th_1 – vertebra

depends heavily on the visco-elasticity of the IVD, the surrounding connective and muscle tissues and their ability to dampen these vibrations.

The frequency response of individual vertebrae monitored on the gymnasts with an extremely heavy-duty top gymnastics training were recorded in the above three phases of the loading regime. On Figure 4, we can see the responses of the individual vertebrae selected in the upper half of the thoracic spine (Th_1–Th_4) excited of C_7.

Monitoring the properties of an AS particular section may be preferable for any of the selected frequencies. In our case, the frequency with the greatest response to a C_7 (about 140 Hz) was selected (Figure 4)

We defined the contractual damping coefficient ***b*** using the size dependence of amplitudes of the individual vertebrae monitored at the resonant frequency of 140 Hz (Figure 5) given by equation (1).

B. Viscosity determination of the vertebrae selected

1. We only evaluated the excited vertebrae, i.e., in our case vertebra C_7 and the four neighboring vertebrae, i.e., Th_1–Th_4.
2. We selected the frequency, which corresponds to the strongest response (resonance) at C_7 at the measuring uplink (up) and downlink (down), e.g., $\Omega = \omega_{r1} = \omega_1 = 140$ Hz for C_7.
3. We deducted the size of the response to C_7, i.e., a_1, that we thought was a reference value and for the surrounding vertebrae Th_1, Th_2, Th_3, Th_4 we found the values a_2, a_3, a_4, a_5. From all the measured values, we calculated their mean values

$$\overline{a}_i = \frac{1}{6}\sum_{j=1}^{6} a_j \,, \qquad (3)$$

and according to the equation (2) we calculated the corresponding viscosity values.

In Table 1, the responses of respective vertebrae both in the ascending and descending measurement modes are recorded, and according to the methodology above, the viscosity values are determined among the AS individual sections, including the reference section average viscosity of the thoracic spine C_7–Th_4. The viscosity calculation was carried out according to the relation (2) for the tissue density. For the calculation simplicity, in this case of methodological studies we assumed that all the vertebrae are of the same length, i.e., $l_1 = l_2 = l_3 = l_4$, and that the tissue density is equal to the water density. The results of the viscosity specific parameters, or their trend, respectively, will be significantly affected by this simplification.

Assuming the same IVD material properties along AS (assumption of linearity), the attenuation should match the relation (1); the wave damping in a homogeneous (long enough) "stick" is exponential. The changes to the viscosity values measured are influenced by the vertebrae of different lengths and the IVD different characteristics and also the in homogenity of the ligamentous carapacealong AS.

The detected values at Th_1 should be considered with caution, since thesemay be affected by the excitation proximity to C_7.

In the same manner, the data from the other modes were evaluated, i.e., immediately after the loading and **the next day, after a night's rest**, just before the next training. The dynamics of changes in the searched parameters, the damping coefficient ***b*** and viscosity ***μ*** in the given modes is shown in the summary Table 2.

RESULTS AND DISCUSSION

From the detected results and the mathematical evaluation of the experiment, it is clear that, due to extreme loading (3.5 hour training RG), changes occur in the selected parameters of the AS mechanical properties (here the damping coefficient and viscosity). The decrease in both the damping coefficient and viscosity is achieved by the decrease in the amplitudes of the detected mode settings, which means a decrease of the AS damping ability as a whole.

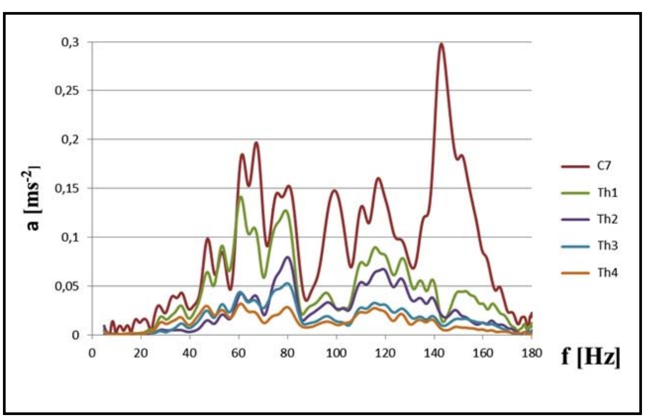

Fig. 4. AS frequency response of the section C_7–Th_4 monitored – before loading

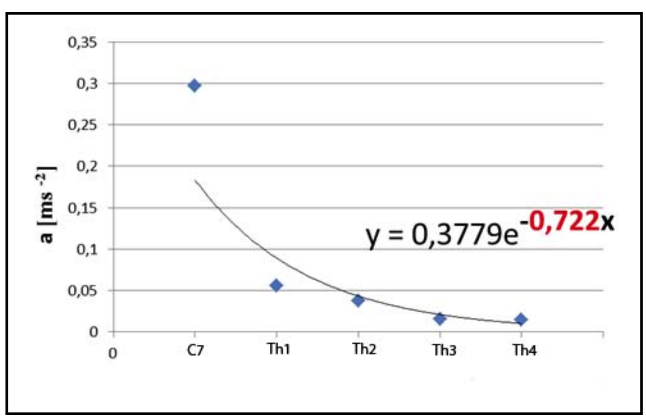

Fig. 5. Dependence of the acceleration size detected at the vertebrae of the spinal segments C_7–Th_4 – before the loading. The coefficient b = 0.772, see the 2nd row in Table 2.

Tab 1. Thoracic spine *ω1* = 140 Hz before the loading.

Vertebr.	No.	Measurement		Responce a_i			$\bar{a}_i$	Length l_i [cm]	ln ($\bar{a}_i$ / $\bar{a}_1$)	μ_i [Pa.s]
C_7	1	a_1	up	0.28	0.30	0.20	0.215	3.5	0	-----
			down	0.17	0.22	0.12				
Th_1	2	a_2	up	0.10	0.06	0.03	0.050	3.5	−1.46	16.2
			down	0.06	0.08	0.06				
Th_2	3	a_3	up	0.05	0.03	0.03	0.045	3.5	−1.6	8.9
			down	0.05	0.07	0.04				
Th_3	4	a_4	up	0.04	0.02	0.02	0.030	3.5	−2.04	**7.5**
			down	0.02	0.03	0.03				
Th_4	5	a_5	up	0.03	0.02	0.01	0.020	3.5	−2.41	6.8
			down	0.02	0.03	0.01				
The viscosity average value of the monitored section C_7–Th_4										9.85

Tab. 2. The dynamics of changes in the damping coefficients **b** and viscosity **μ** of the AS portion selected during the top training of a rhythmic gymnast during 24 hours.

before loading	up	down	$\bar{b}$	$\bar{\mu}$
1.	0.667	0.604		
2.	0.722	0.474		
3.	0.757	0.531		
$\bar{x}$	0.715	0.536	**0.626**	**9.85**
after loading	**up**	**down**	$\bar{b}$	$\bar{\mu}$
1.	0.484	0.309		
2.	0.31	0.213		
3.	0.296	0.33		
$\bar{x}$	0.363	0.284	**0.324**	**2.15**
day after loading	**up**	**down**	$\bar{b}$	$\bar{\mu}$
1.	0.488	0.455		
2.	0.321	0.382		
3.	0.378	0.338		
$\bar{x}$	0.396	0.392	**0.394**	**3.8**

Both the defined values ***b, μ*** assume a similar trend, when the two values score a marked decline after loading and a rise after resting.

A. In the case of ***b*** to 52% and in case of μ to 22% of the starting value, followed by a slight increase after about 18–24 h resting in the case ***b*** to 62% and in case of ***μ*** to 38% of *the starting value.*

B. The increase in value after resting 18–24 h can be also evaluated with respect to *the value after loading.* This comparison reveals that after resting the coefficient ***b*** increases of 22% and the viscosity ***μ*** of 78% values after loading.

It is apparent from the information stated above that the defined parameters show varying degrees of sensitivity to the symptoms investigated and could be advantageously used e.g. to locate a pathology in AS, or a degree of fatigue or resting after i.e. a sport performance, physiotherapy intervention, respectively, etc. The viscoelastic tissues – components forming the AS unit, react to a mechanical load with a decrease in the above parameters and after relaxation, limited within the time interval stated above, the values of the parameters gradually return with different dynamics to the original values.

In terms of the length of time required before the original values are reached corresponding to the values before the AS loading and if at all, or how long it reaches the values "acceptable", this is a question for further experimental work. The return towards the original values will be highly individual, and certainly influenced by genetic and other factors, e.g., regeneration process, eating habits, drinking regime, possibly the use of dietary supplements or other medications.

The regenerative process, and thus a return to the baseline of the component rheological properties, is a matter of optimizing the loading mode without negative effects on the human organism, here gymnasts.

An important result of using the methodology presented by Transfer Vibration through Spine will be the ability to use the AS non-invasive diagnostics for evaluating the load, relaxation and regeneration modes, or medical and therapeutic procedures with a high degree of individualization.

CONCLUSION

The methodology introduced and indicated the ability of AS quality assessment using quantitative analysis. These trends changed in the selected parameters and will continue to be scrutinized to a greater number of homogeneous groups of probands including statistical evaluation.

The objective of the study is to show the possibilities of the TVS method to identify and classify the AS immediate changes manifested after mechanical load. The authors of the studies tend to determine whether the changes in the properties of AS connective tissues are identifiable by TVS and whether their quantification is also possible, regardless of the age and nature of the applied load.

ACKNOWLEDGEMENT

This project was supported by grants PRVOUK 38, SVV 2016 - 260346, GAUK962314

REFERENCES

1 Adams MA, Dolan P, Hutton WC, Porter RW (1990). Diurnal Changes in Spinal Mechanics and Their Clinical-Significance. Journal of Bone and Joint Surgery-British Volume. **72**(2): 266–270.
2 Adams MA, McNally DS, Dolan P (1996). 'Stress' distributions inside intervertebral discs – The effects of age and degeneration. Journal of Bone and Joint Surgery-British Volume. **78B**(6): 965–972.
3 Cupisti A, D'Alessandro C, Evangelisti I, Umbri C, Rossi M, Galetta F, Piazza M (2007). Injury survey in competitive sub-elite rhythmic gymnasts: results from a prospective controlled study. J Sports Med Phys Fitness. **47**(2): 203–207.
4 Frobin W, Brinckmann P, Kramer M, Hartwig E (2001). Height of lumbar discs measured from radiographs compared with degeneration and height classified from MR images. [Clinical Trial Comparative Study Randomized Controlled Trial]. Eur Radiol. **11**(2): 263–269.
5 Gouttebarge V, Inklaar H, Frings-Dresen MH (2014). Risk and consequences of osteoarthritis after a professional football career: a systematic review of the recent literature. [Review]. J Sports Med Phys Fitness. **54**(4): 494–504.
6 Helge EW, Kanstrup IL (2002). Bone density in female elite gymnasts: impact of muscle strength and sex hormones. [Clinical Trial Controlled Clinical Trial]. Med Sci Sports Exerc. **34**(1): 174–180.
7 Hutchinson MR (1999). Low back pain in elite rhythmic gymnasts. Med Sci Sports Exerc. **31**(11): 1686–1688.
8 Jelen K, Klouckova K, Zeman J, Kubovy P, Fanta O (2012). Changes in attenuation characteristics of axial system of pregnant drivers detected by the TVS method. [Research Support, Non-U.S. Gov't]. Neuro Endocrinol Lett. **33**(4): 462–468.
9 Jelen K, Šorfová M, Tlapáková E, Billich R (2013). Biomechanical reflection of human hypokinetic stress and its identificators. Prague: Karolinum Press.
10 Jelen K, Zeman J, Kubový P, Drahorádová R, Holub T (2010). Dynamic of Transfer Characteristic of Driver´s Body Biocomponents During Vehicle Driving. In: Otáhal S, Denk F, Holub O (Ed.), Spinal complexity and its biomechanical reflection (pp. 131–141). Brno.
11 Kerssemakers SP, Fotiadou AN, de Jonge MC, Karantanas AH, Maas M (2009). Sport injuries in the paediatric and adolescent patient: a growing problem. [Review]. Pediatr Radiol. **39**(5): 471–484. doi: 10.1007/s00247-009-1191-z.
12 Lyons G, Eisenstein SM, Sweet MB (1981). Biochemical changes in intervertebral disc degeneration. [Research Support, Non-U.S. Gov't]. Biochim Biophys Acta. **673**(4): 443–453.
13 Machač D (2011). Modeling of spinal chord under dynamical loading., Czech Technical University in Prague, Prague.
14 Maršík F, Dvořák I (1998). Biotermodynamika, Praha.
15 Maršík F, Zeman J, Jelen K (2010). Analysis of transmission of vibration trough the spine, measured by TVS method. Prague: Faculty of Physical Education and Sport, Department of Anatomy and Biomechanics.
16 McNally DS, Shackleford IM, Goodship AE, Mulholland RC (1996). In vivo stress measurement can predict pain on discography. Spine. **21**(22): 2580–2587.
17 Panská Š, Petr M, Jelen K (2013). The Influence of Hypo-hyper Kinetic Loading of the Human Musculoskeletal System on Bone Tissue Quality and its Genetic Predispositions. In Jelen K, Tlapáková E, Šorfová M, Billich R (Ed.), Biomechanical Reflection of Human Hypokinetic Stress and its Identificators. Praha (pp. 105–130). Praha: Karolinum Press.
18 Papavasiliou A, Siatras T, Bintoudi A, Milosis D, Lallas V, Sykaras E, Karantanas A (2014). The gymnasts' hip and groin: a magnetic resonance imaging study in asymptomatic elite athletes. [Comparative Study]. Skeletal Radiol. **43**(8): 1071–1077.
19 Postacchini F, Gumina S, Cinotti G, Perugia D, DeMartino C (1994). Ligamenta flava in lumbar disc herniation and spinal stenosis. Light and electron microscopic morphology. [Comparative Study]. Spine (Phila Pa 1976). **19**(8): 917–922.
20 Putzer M, Ehrlich I, Rasmussen J, Gebbeken N, Dendorfer S (2016). Sensitivity of lumbar spine loading to anatomical parameters. J Biomech. **49**(6): 953–958.
21 Tanchev PI, Dzherov AD, Parushev AD, Dikov DM, Todorov MB (2000). Scoliosis in rhythmic gymnasts. Spine (Phila Pa 1976). **25**(11): 1367–1372.
22 Tournis S, Michopoulou E, Fatouros IG, Paspati I, Michalopoulou M, Raptou P, Pappaioannou N (2010). Effect of Rhythmic Gymnastics on Volumetric Bone Mineral Density and Bone Geometry in Premenarcheal Female Athletes and Controls. The Journal of Clinical Endocrinology & Metabolism. **95**(6): 2755–2762.
23 Urban JPG, McMullin JF (1988). Swelling pressure of the lumbar intervertebral discs: influence of age, spinal level, composition, and degeneration. Spine (Phila Pa 1976). **13**(2): 179–187.
24 Urban JPG, Roberts S (2003). Degeneration of the intervertebral disc. Arthritis Research & Therapy. **5**(3): 120.
25 van Dieen JH, Selen LP, Cholewicki J (2003). Trunk muscle activation in low-back pain patients, an analysis of the literature. [Research Support, Non-U.S. Gov'tResearch Support, U.S. Gov't, P.H.SReview]. J Electromyogr Kinesiol. **13**(4): 333–351.
26 Zander T, Dreischarf M, Schmidt H (2016). Sensitivity analysis of the position of the intervertebral centres of reaction in upright standing – a musculoskeletal model investigation of the lumbar spine. Med Eng Phys. **38**(3): 297–301.