NEW APPROACH TO IDENTIFICATION OF INTERVERTEBRAL DISC MECHANICAL PROPERTIES

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Abstract: This article describes the original measuring method and its results aimed at identifying the character of viscoelastic forces in the respective motion components and their mutual interactions. The method is based on the identification of the motion of a freely oscillating object placed in a center comprising the intervertebral disc when using the step mechanical excitation in the specific direction. The research was carried out on ovine and porcine intervertebral discs. The measurements were performed safely within the physiological range of motions and using as fresh a sample as possible free of preservatives. The result so far is a mathematically precise and original description of the non-linearity of stiffness, verification of linearity of the viscous component, and a promising description of interaction properties with the individual degrees of freedom.

Keywords: intervertebral disc, spinal disc, attenuated oscillations, free oscillations, viscoelasticity, stiffness, intervertebral disc replacements.

Introduction

The method is based on the determination of parameters for kinetic energy transmission in the intervertebral disc as a whole. We are trying to describe the intervertebral disc using only several (up to 15) parameters irrespective of the internal structure complexity of the examined object. We consider this trend to be useful especially with respect to its anticipated future practical use, for example for the creation of disc replacements. Currently available replacements are designed using absolutely unacceptable premises and simplifications [10]. We believe that only those replacements with external viscoelastic anisotropic parameters as similar to the original as possible (and in combination with a suitable inert material) can cause minimal response from the body in the form of adjustments of the surrounding muscular and ligamentous structures, so that these structures are not overloaded, and the vertebrae will not have to create osteophytes as a compensation of unsuitable load distribution [4].

In view of the foregoing, we decided to perform a detailed examination of the area of very small motion amplitudes. The ranges of the motion and forces applied were situated deeply in the physiological area, as we believe that exactly this area is most frequently used during everyday life; therefore we must consider this area as much as possible when designing the replacement as we know that bone remodeling causes only periodical, permanently present changes rather than extreme conditions which are very rare [5, 9]. Our focus on this area brought surprising results. We have obtained a mathematical description of the non-linear effect of stiffness during low amplitudes, or in more detailed terms, a characterization of stiffness when the stiffness decreases with increasing amplitude in the area of small deviations. We have created a differential equation describing oscillations in this area with the potential corresponding to the function (2).

This potential describes relatively faithfully the character of stiffness in the area of small deviations, directly contradicting the statements of some authors who study the issue of determination deformation characteristics of intervertebral discs [8, 6, 2].

Attenuation capacity is the basic property of spinal discs [11]. This organ is very well equipped for this function. It is not only capable of transmitting only approximately 80% of incoming impact energy but it also sustains almost no fatigue from it as the absorbed energy is distributed evenly to all degrees of freedom in the disc. This was at least demonstrated by preliminary results of the evaluation method, which is the second topic of this article. While we are using a balance beam system to determine the character of stiffness and attenuation in the respective directions with momentum parameters enabling us to carry out the entire attenuation process virtually at the level of excitation (fig. 2), the measurement apparatus in the latter is modified to envisage the transmission of energy between the individual directions of attenuating oscillations (fig. 5).

In this article, we will try to outline the method for the characterization of external parameters of the disc as a whole as the minimum set of parameters to determine the character of the disc (or replacement) intervertebral junction.

Material and Methods

We used samples of ovine *(ovis domestica)* and porcine *(sus scrofa)* lumbar and throracic spine, or in more detailed terms, spinal movement unit (vertebra-disc-vertebra) removed from muscles and ligaments (fig. 1) as a material biomechanically equivalent to the human intervertebral disc [3, 12]. For most measurements, we made an incision through the intervertebral joints to remove the dorsal parts of the sample, including the spinal canal. Animals of similar age were slaughtered to obtain the samples (*ovis domestica*, males 3 to 6 months old; *sus scrofa*, males 9 to 12 months old). The animals were provided and slaughtered by Jan Ruzicka, a private agricultural firm from Slivenec, Prague. To eliminate the bias caused by preservation, we used preservative-free samples only and the measurements were performed as soon as possible after the slaughter (mean time 8 hours after the slaughter). For repeated measurements, samples were dampened with a Ringer solution to avoid excessive dehydration.

Figure 1: Samples of ovine spine units prepared for measurements.

To determine the character of the viscoelastic elements and substitute structure of the disc mass as a whole, we analyzed the attenuating function of free oscillations excited by delta pulses in the direction of flexion, lateral flexion, and torsion. The axial direction was not investigated in our study as the effective stiffness in this direction is by two orders of magnitude higher compared to the other directions, and the measurement apparatus would require a different mechanical construction and would have to be equipped with a transducer and higher sampling frequency. The final version of the device developed for this measurement is shown in (fig. 2).

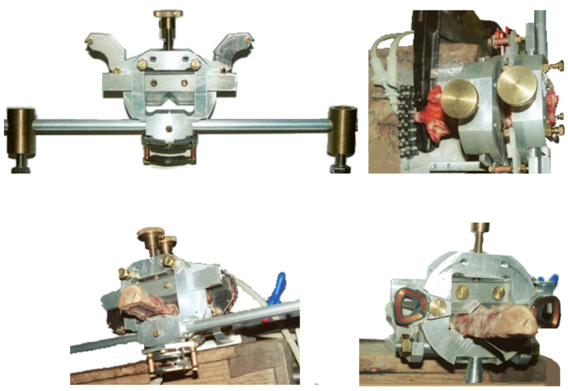

Figure 2: Final version of the measurement apparatus.

The apparatus comprises a part for the fixation of the first vertebra body to a fixed, immobile support plate and the second part which connects to the body of the adjacent vertebra a torque-bar and permanent magnets that form a movable part of the detectors of the balance beam (torque bar) motion rate. Different weights were symmetrically put on the torque bar determining both the preload and the torque of the oscillator. Symmetrically placed coils of the detectors allow for the induction of motions for example using a periodical signal from a low-frequency generator. The signal from the coils is transmitted to the 16 bit AD transducer DRAK5 (PaPouch, s.r.o.). A digitalized signal was recorded via a serial port of the personal computer with the Linux operation system. The sampling frequency was 1000 (samples/sec) for all measurements. When using this construction with a large non-symmetric defining momentum, the attenuation occurs almost in a single plane, and we can solve the problem unidimensionally. The example of the attenuation curve is shown in (fig. 3).

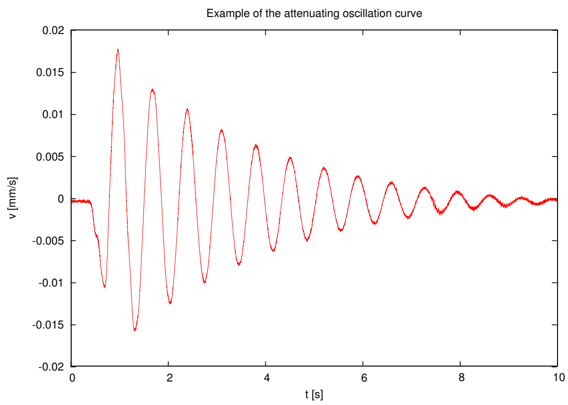

Figure 3: Example of the attenuating oscillation curve.

Analysis of this curve revealed that more than 99% $\pm$ 1% attenuation energy is absorbed by means of linear viscous mechanism. For a description of the attenuation rocess, it was sufficient to describe the system using an alternative scheme corresponding to the Kelvin scheme. However, the stiffness was highly non-linear. We found out that the attenuating process can be described with the differential equation as follows (1):

$$m\ddot{x} + \nu\dot{x} + k_0\left(1 + \frac{a}{\sqrt{1+bx^2}}\right)x = 0, \qquad (1)$$

where $m, \nu, k_0, a, b \in \Re^+$,

or we have to solve the equation (2) of the attenuated pendulum with the potential

$$U(x) = \frac{k_0}{2}x^2 + a\sqrt{1+bx^2}, \qquad (2)$$

The following (fig. 4) shows the example of the best possible fit of data obtained from measurements by solving the differential equation of the attenuated pendulum with a classical parabolic potential and a potential selected by us and defined by the equation (2). Solving and finding of optimal linear coefficients of the equation was performed using the Runge-Kutte method in the Octave program.

We have modified the apparatus to visualize the transfer of energy between the components (fig. 5).

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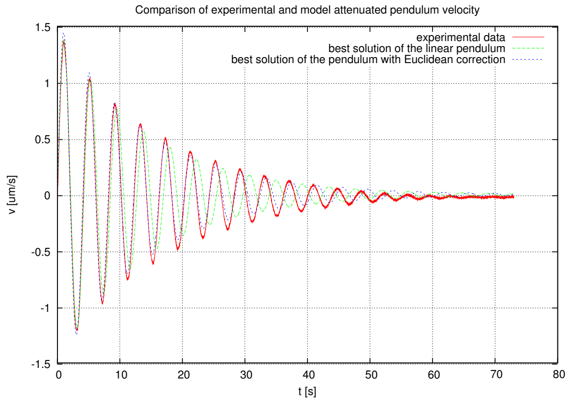

Figure 4: Comparison of experimental data (sus scrofa, L4-5, torsion) of the planar pendulum with the center formed by the intervertebral disc with the best possible solving of the mathematical pendulum equation $\ddot{x}+0,14\dot{x}+2,2x=\delta$ and best possible solving with potential 2 of the equation $\ddot{x}+0,145\dot{x}+2,21x+\frac{0,1}{\sqrt{1+x^2}}=\delta$.

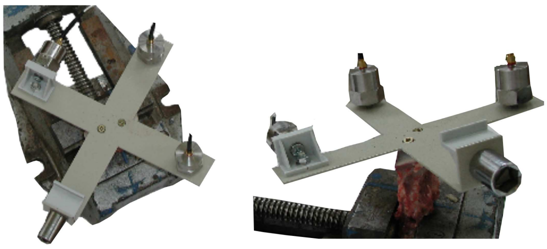

Figure 5: Apparatus modified to visualize the transfer of energy between the components.

The swing yard was replaced by the symmetric oscillating cross with a 20 times less moment of movement than the flat moment of attenuation. Three mutually perpendicular piezoelectric detectors sensing the acceleration of the cross in the three components of the swing were placed at the end of the cross arms. Excitation had the character of delta pulses again. The detectors were connected to the AD transducer via a charge amplifier. Typical records are seen in (fig. 7). The functional model of this issue is shown in (fig. 6).

We have of course no primary knowledge of the character of symmetry of junctions. Being inspired by the analysis of the unidimensional case, where we found out that the linear approximation is a good initial step to describe the system, we first tried to analyze these curves within the linear model also in this case. Let‘s take the equations (3) that can be rewritten into a set of six linear differential equations of the first order (4) [14]. This indicates the existence of three eigenvalues, or three eigenvectors or modes of excitation, for which the entire attenuation process will proceed with a repeating periodicity, but with decreasing amplitude. These three eigenvalues certainly correspond to the natural frequencies of oscillation in the three orthogonal directions. Reconstruction of the parameters of differential equations is the subject of our current efforts. To date, we have successfully completed this step only in a few special cases.

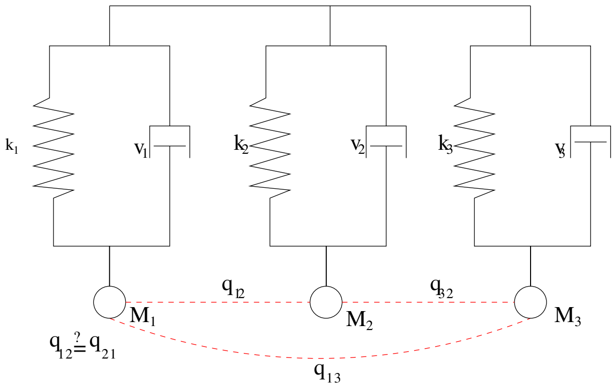

Figure 6: The functional model of the spine movement unit.

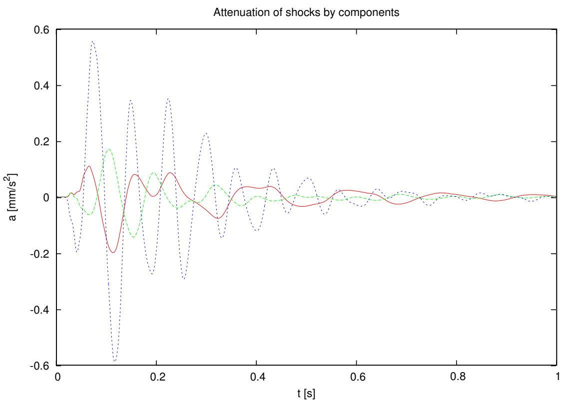

Figure 7: Records of acceleration in the respective motion components. We can see the transfer of kinetic energy in this case from the excited torsion component (blue) into the flexion component (green) and lateral flexion component (red).

$$\begin{aligned}\ddot{x} &= -\kappa_{11}x-\nu_1\dot{x}-\kappa_{12}y-\kappa_{13}z\\ \ddot{y} &= -\kappa_{22}y-\nu_2\dot{y}-\kappa_{21}x-\kappa_{23}z\\ \ddot{z} &= -\kappa_{33}z-\nu_3\dot{z}-\kappa_{31}x-\kappa_{32}y\end{aligned} \tag{3}$$

$$\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\\ \dot{x}_5\\ \dot{x}_6\end{pmatrix}=\begin{pmatrix}0&0&0&1&0&0\\ 0&0&0&0&1&0\\ 0&0&0&0&0&1\\ -\kappa_{11}&-\kappa_{12}&-\kappa_{13}&-\nu_1&0&0\\ -\kappa_{21}&-\kappa_{22}&-\kappa_{23}&0&-\nu_2&0\\ -\kappa_{31}&-\kappa_{32}&-\kappa_{33}&0&0&-\nu_3\end{pmatrix}\begin{pmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\\ x_6\end{pmatrix} \tag{4}$$

or better

$$\begin{aligned}\ddot{x} &= -\kappa_{11}x-\nu_1\dot{x}-(x-y)\kappa_{12}-(x-z)\kappa_{13}\\ \ddot{y} &= -\kappa_{22}y-\nu_2\dot{y}-(y-x)\kappa_{21}-(y-z)\kappa_{23}\\ \ddot{z} &= -\kappa_{33}z-\nu_3\dot{z}-(z-x)\kappa_{31}-(z-y)\kappa_{32}\end{aligned} \tag{5}$$

where $\kappa_{ij}=\kappa_{ji}$

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Results

Reconstruction of the potential from experimental data:

The shape of the potential depression can be theoretically examined directly from the experimental data. We proceeded based on the data measured for single-component motion (fig. 8).

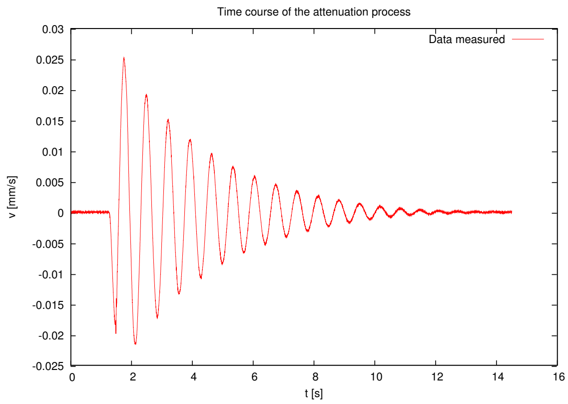

Figure 8: Time course of the attenuation process.

After the subsidence of the excitation impact (δ pulse), the energy in our system is dissipated and no more energy flows into the system. According to all facts known to date, the energy in our system is dissipated solely by viscous forces, i.e., the forces proportional to the immediate velocity. As we determine the velocity curve during the experiment, we are able to determine the total energy in the system vs. time dependence. The total energy in the system is formed by potential energy and kinetic energy. In this relation, we know the course of total energy $E(t)$ and we can use velocity to determine kinetic energy $T(t) = \frac{1}{2}mv^2(t)$. The only unknown functional dependence in the equation is time course of potential energy $U(t)$. The total energy absorbed is determined by the equation (6) [1]:

$$\int_0^x F_v(t)dx, \tag{6}$$

where F_v is the time course of viscous force.

Lets substitute $F_v(t) = \nu v(t)$ for viscous force and change the integral of distance for the integral of time. We obtain the following equation (7) for the energy absorbed:

$$T(t) = \int_0^t \nu v(t)v(t)dt = \nu \int_0^t v^2(t)dt \tag{7}$$

The total mechanical energy at the given time is:

$$E(t) = E_0 - \nu \int_0^t v^2 dt, \tag{8}$$

where $E_0, \nu \in \Re^+$ is the initial energy delivered into the system by means of a delta pulse.

The example is shown in (fig. 11). The entire potential energy equation reads:

$$U(t) = E_0 - \nu \int_0^t v^2(t)dt - \frac{1}{2}mv^2(t) \tag{9}$$

Given the zero potential energy requirement during each pass of the pendulum through the equilibrium position, we obtain the following condition for the coefficients in the equation. Times t_i are defined by the condition:

$$x(t_i) = 0, \ \forall\, t_i \text{ je } E_p(t_i) = 0 \tag{10}$$

The situation for suitable coefficients found is documented in (fig. 9).

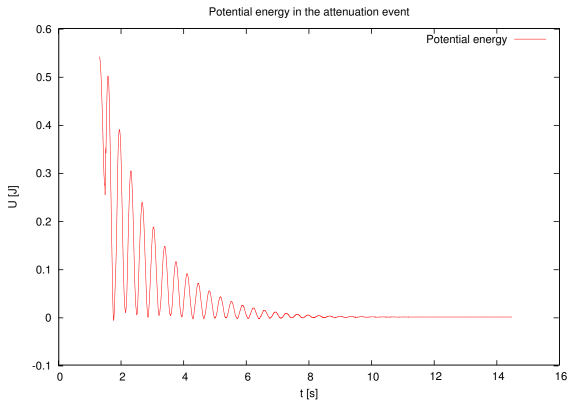

Figure 9: Potential energy in the attenuation event.

By integrating the velocity measured, we will get the position of the pendulum in time $x(t) = \int_0^t v(t)dt$ see (fig. 10).

We can also plot the potential energy vs. deviation dependence into the graph and thus clearly see the potential depression (fig. 12).

For the purpose of comparison, (fig. 12) shows the potential energy fit by the best possible parabola in the meaning of minimum deviation squared. The graph of size of these deviations vs. amplitude is shown in (fig. 13).

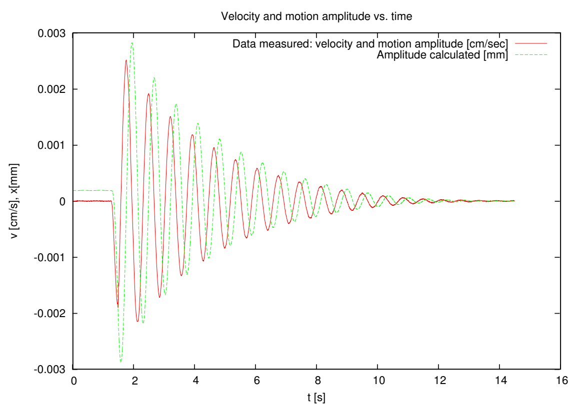

Figure 10: Velocity and motion amplitude vs. time.

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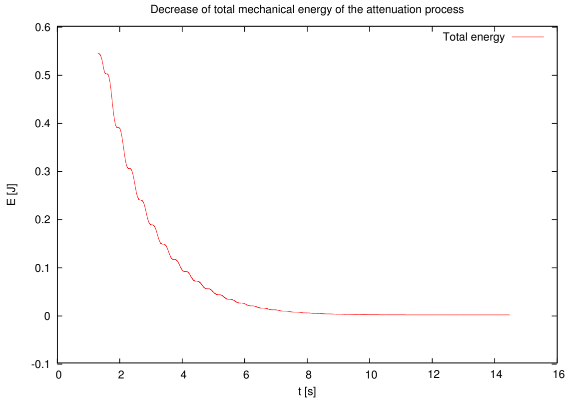

Figure 11: Decrease of total mechanical energy of the attenuation process.

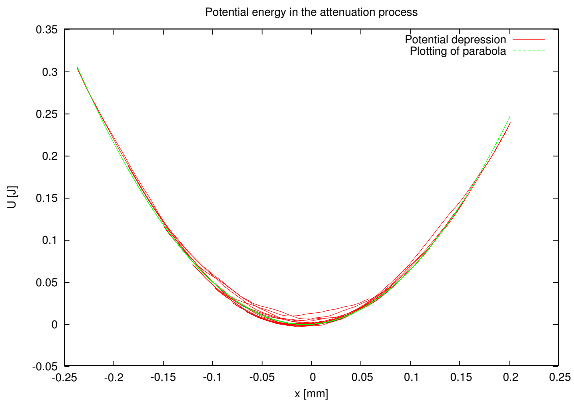

Figure 12: Potential energy in the attenuation process.

Discussion

Generally, stiffness independent of the amplitude of motion or increasing with the amplitude is anticipated in the intervertebral disc models. This work shows that this applies only for amplitudes at the upper values of the physiological range or even beyond it. However, exactly the opposite, i.e., softening with increasing amplitude, clearly applies in the area of small deviations deeply in the Panjabi neutral zone [13], the existence of which we are questioning. It is unquestionable that different measurement methods should be used for the determination of viscoelastic properties of the intervertebral disc. The objective of our relatively unconventional method includes but is not limited to an impartial and maximally effective identification of the group of parameters describing, to the best extent possible, the main properties of the disc in the area of its most frequent use. Certain unconventional parameters which we are proposing for the evaluation of differences both in authentic discs and in intervertebral implants, such as coefficients a, b, for which we have no idea about which real directly measurable parameters they could correspond with, can somewhat provoke some avowed mechanical engineers, but we consider them to be very useful.

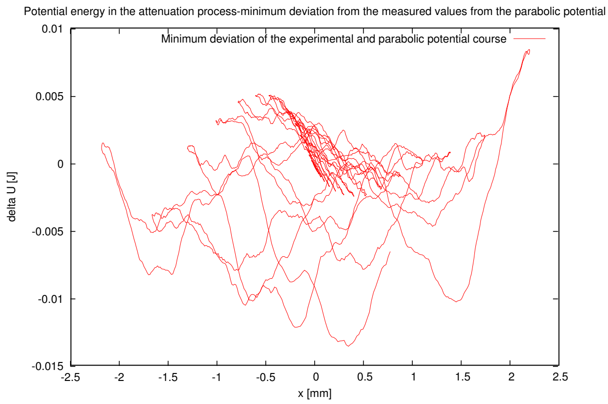

Figure 13: Potential energy in the attenuation process-minimum deviation from the measured values from the parabolic potential.

Conclusion

Using the method of free oscillation, which we consider to be more suitable for the determination of viscoelastic properties of the intervertebral disc as a whole, rather than conventional tear-off techniques [3], we have identified the non-linear stiffness in the area of small physiological oscillations for flexion and rotation. Using detailed analysis of the attenuation curve, we determined a relatively successful correction of the potential in the mathematical attenuated pendulum equation. This component has the character of calculation of distances in the Euclidean space. This corrective component describes the major part of the stiffness character, i.e., softening of the material during larger deviations.

By modifying the measuring apparatus, we have obtained the opportunity to experimentally examine the inter-directional energy transfers within a single attenuation process. We are convinced that these transfers significantly contribute to the distribution of load into all substructures of the disc and thereby to the higher resistance thereof, as well as to the maximum attenuation effect.

Since we are aware of the principal non-linearity of the disc‘s character, we try to initially describe the interdirectional transfer of mechanical energy in the disc as a linear equation system, which enables us to determine three eigenvalues of frequency and three eigenvectors of the disc system which, as could be anticipated, give a result almost co-linear with the main symmetry axis of the disc.

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