Národní konference s mezinárodní účastí

INŽENÝRSKÁ MECHANIKA 2002

13. – 16. 5. 2002, Svratka, Česká republika

BIOMECHANICS OF SPINE UNDER CORRECTION BRACE EFFECTS

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Abstract

The topic of this paper is a computer simulation of treatment of children spine deformities with braces (orthosis). Orthopaedists in the Czech Republic use corrective braces of type Cheneau or Cerny. The brace has force effects on a child skeleton. First, the negative plaster form of a child trunk is made and then the positive plaster form is created. The orthopaedist determines the loading place and the plaster form is deepened in this place. The laminate brace made according to this plaster form pushes the child trunk (like a tight shoe).

The research is supported by a grant of the Czech Grant Agency No. 106/00/0006 "Functional Adaptation and Pathobiomechanics of Limb and Axial Skeleton under Force Effects". The paper shows the manner of determination of the stress state in vertebrae and inter-vertebra discs and the solution of the spinal curve correction under brace force effects for a concrete child patient. The project searches the dependence of the activation and velocity of the spinal curve correction in the spinal stress state for many patients. It means that the paper shows the computing algorithms for spinal deformations and the stress state under brace force effects and the simulation of the spinal curve correction.

Louis's model of the spine is used. The breast curve classification can be used according to King. Note that the brace of type Chenau is recommended for the spinal curve type King I, II, and IV and the brace of type Cerny for the spinal curve of type King II, III a V.

The spinal deformations are solved by the finite element method as a beam (spine) in an elastic ground (soft tissue) loaded by given displacements or by the finite element method using vertebrae, inter-vertebra discs and soft tissue elements. The 1st method is described in the article.

The calculation algorithm and parameters are verified with treatment courses. The sensor plates put into braces have measured the load values between the brace and the child trunk surface. The simulation program assesses the spinal curve correction according to the spinal stress state and the time for which the brace has been used.

Key words: biomechanics, simulation of treatment, scoliosis, spine stress state, spine remodelling

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1 Introduction

Spinal corrective braces (see fig. 1) are used for treatment of spine scoliosis of children (pathologic deformation of the chest curve). The X-ray of the patient from fig. 1 without and with the brace is shown in fig. 2. The dynamic corrective braces of type Cheneau or according to Cerny's patent No. 281800CZ (see fig. 1) are usually used in the Czech Republic. The breast curve can be classified according to King. The brace of type Chenau is recommended for the spinal curve of type King I, II, and IV and the brace of type Cerny for the spinal curve of type King II, III a V.

Fig. 1. Patient without and with the dynamic corrective brace according to Cerny's patent No. 281800CZ.

The brace pushes the child trunk and makes a stress state in the patient's spine. The brace changes the spinal curve; it means that the spinal pathologic form is corrected. After a long–term use of the brace, the part of spinal correction is permanent. The brace is made in the following manner: first, a plaster negative form and then a positive form of the child trunk are made. The orthopaedist's assistant according to his experience and the orthopaedist's recommendation deepens the plaster positive form in the place where the brace has to push on the child's trunk. The plastic brace is then made according to this plaster form. After its application on the child trunk the brace pushes the places where the form has been deepened (the tight shoe principle).

If computer search is not used, the brace force effect is the result of the orthopaedist and his assistant's experience only and it does not ensure that the designed brace form and the manner of treatment are optimal. The paper shows computer algorithms which is able to determine the stress state in vertebrae and inter-vertebrae discs and spinal curve changes for the concrete brace applications. The theoretical conclusions are made according to many treatment courses. The remodelling of the spine pathologic curve depends on a spine stress state, time and manner of the brace application. The treatment course is simulated on the computer. The aim of the research is the determination of an ideal brace form and a treatment course with the help of computer simulation. The computer program calculates the spine stress state and its curvature changes at each time point. The treatment simulation is now provided contemporaneously with the patient's cure and the computer model is verified. If the computer model and treatment reality will have the same behaviour, then the model can be used for the treatment prognosis in the orthopaedic praxis. Since the treatment course takes a long time, the simulation model is still verified so that its prognoses can be as precise as possible.

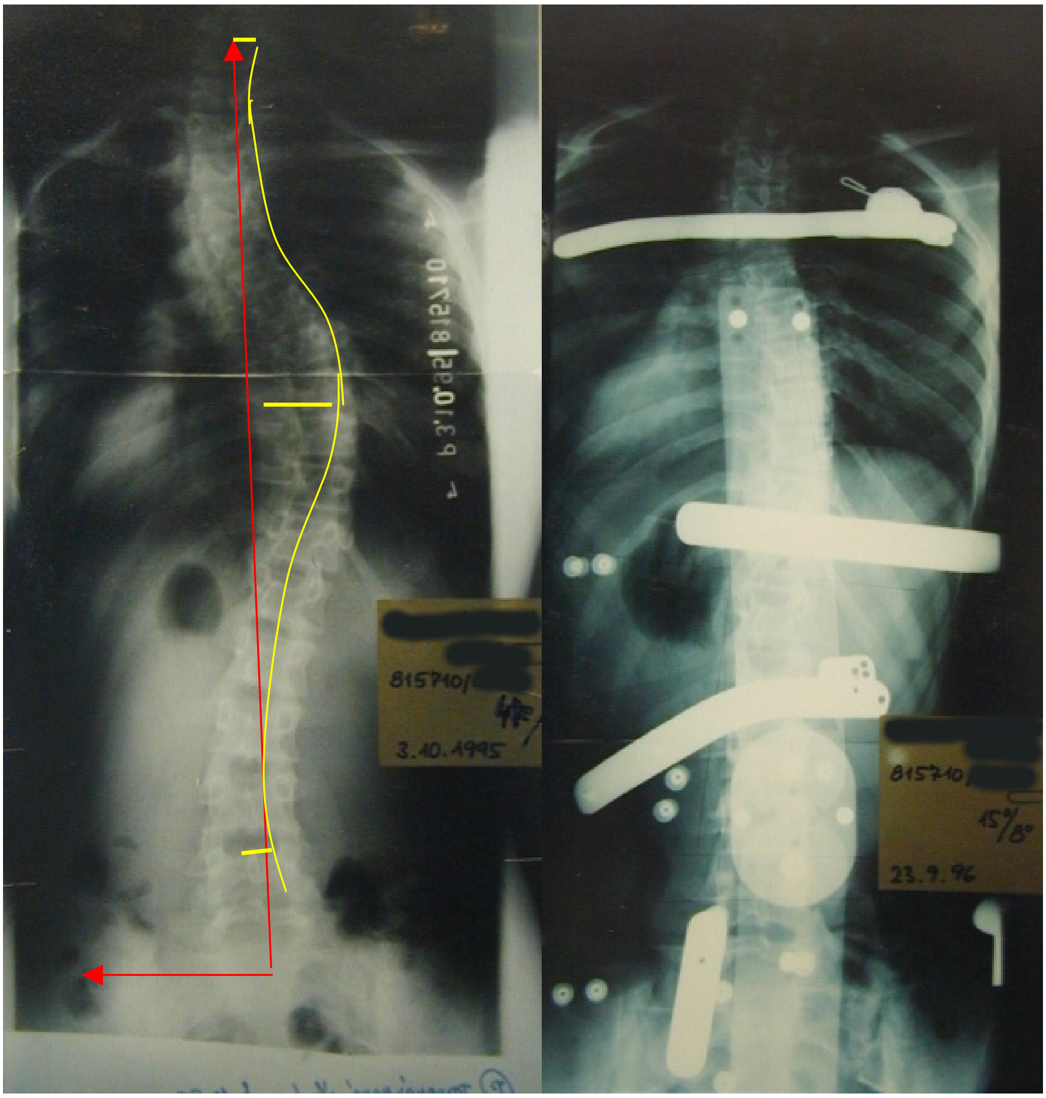

Fig. 2. The frontal X-ray of the patient from fig.1 without and with the corrective brace.

2 Spinal Curve

The task is solved using Cartesian coordinates (x – spine axis direction, y,z – frontal and sagital plane). The spinal curve is stored in the computer as the following 3 functions

$$y = y(x),\ \ z = z(x),\ \varphi = \varphi(x), \tag{1}$$

where φ is the turning according to the x-axis. The spinal curve can be described if the extreme values of y and/or z are measured from X-ray (the extremes of the yellow curve in the left X-ray in fig.2). The method is applied for the frontal and sagital plane, too. The spinal curve has 3 extremes of coordinates maximum. The curve is divided into n sectors between the coordinate beginning, extremes and the end point, respectively (max. n is 4). The extreme coordinates x_i, y_i, $i=1,...,n-1$ and the coordinate x_n of the spine end (spine length where $x_n = 0$) are measured by X-ray (see fig 2). The length of segment i is

$$l_i = x_i - x_{i-1},.$$

The local coordinate ξ is considered from the beginning of segment i. The function y is considered as polynomial. It is for the 1[st] segment (quadratic polynomial function)

$$y = \frac{y_i}{l_i}\xi\left(2 - \frac{\xi}{l_i}\right),$$

for the inner segments (cubic polynomial function)

$$y = y_{i-1} + \frac{(y_i - y_{i-1})\xi^2}{l_i^2}\left(3 - 2\frac{\xi}{l_i}\right)$$

and for the last segment (quadratic polynomial function)

$$y = y_{i-1}\left(1 - \frac{\xi^2}{l_i^2}\right).$$

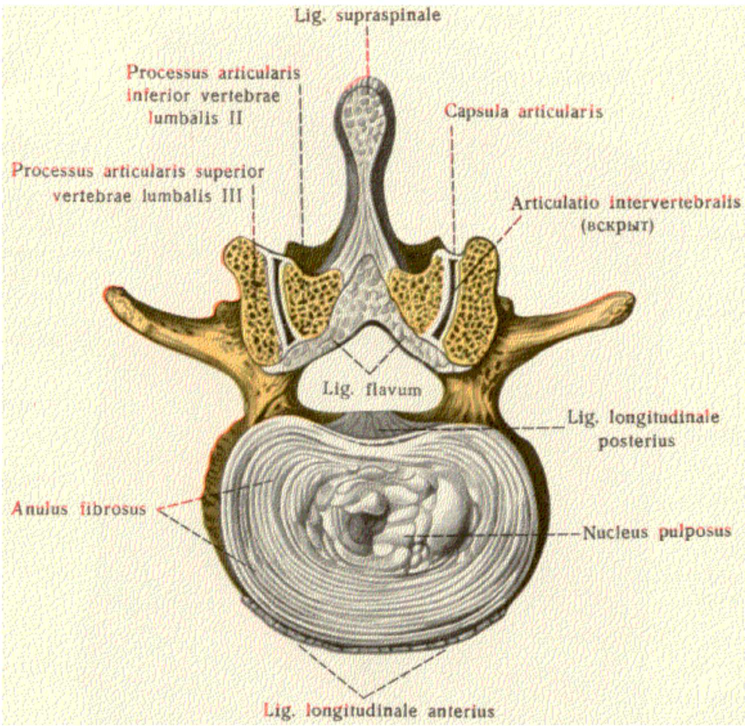

Fig. 3. Inter-vertebrae disc and lignums.

The function values on the segments i - 1 and i boundary are equal to y_i and their derivates equal zero. The same approximation can be used for z coordinate. The functions *y,z* describe the spine initial position which is changed in each iteration step. The deformations of the spinal curve in the vertebrae centres as a force effect of the brace are added to the spine position from the last iteration step.

2 Deformation of the Spinal Curve

The inertia moment has to be determined for an inter-vertebrae disc and lignums cross-section area (see fig. 3). The calculation procedure is as follows: the cross-section area is divided into triangles and one third of triangle areas are concentrated to their side centres.

The spine is solved as a beam in an elastic basis and the finite element method (deformation variant according to Lagrange principle) is used for the stress state calculation. It is supposed that the vertebrae have no deformation. The potential energy is calculated for the inter-vertebrae discs volume and for the pressed soft tissue region of a child trunk. The width of the soft tissue is for simplification considered constant (rectangle cross-section of the trunk). The displacements and turning at vertebrae centres are kinematic unknowns:

$$r = \begin{Bmatrix} r_1 \\ r_2 \end{Bmatrix},\ r_1^T = \left[\varphi_{x,,i}, \varphi_{x,i+1}\right],\ r_2^T = \left[w_i, \varphi_i, w_{i+1}, \varphi_{i+1}\right], \tag{2}$$

where φ_x are turnings according to the spine axis. The following algorithm is valid for the frontal and sagital planes, the planes will not be indicated by the plane index.
The stiffness matrix for the spine part between the centres of neighbouring vertebrae is (torsion and beam influences)

$$K = \begin{bmatrix} K^1 & 0 \\ 0 & K^2 \end{bmatrix}. \tag{3}$$

The sub-matrixes will be determined separately for deformation of the spine and for soft tissue.

3.1 Deformation of Inter-Vertebrae Discs

The beam and torsion stiffness is

$$k = \frac{2EI}{l},\quad t = \frac{GI_T}{l},$$

where E,I are the modulus of elasticity and the moment of inertia of a cross-section of the inter-vertebrae disc and lignums (see fig. 3) and l is the thickness of the disc. The torsion influence is:

$$K^1 = \begin{bmatrix} t & -t \\ -t & t \end{bmatrix}. \tag{4}$$

The influence for $\overline{R}$ - forces (moments) and $\overline{r}$ - movements (turns) on inter-vertebrae disc boundaries are

$$\overline{R}_2 = \overline{K}^2 \overline{r}_2\ , \tag{5}$$

$$\overline{K}^2 = \begin{bmatrix} \frac{6k}{l^2} & -\frac{3k}{l} & -\frac{6k}{l^2} & -\frac{3k}{l} \\ -\frac{3k}{l} & 2k & \frac{3k}{l} & k \\ -\frac{6k}{l^2} & \frac{3k}{l} & \frac{6k}{l^2} & \frac{3k}{l} \\ -\frac{3k}{l} & k & \frac{3k}{l} & 2k \end{bmatrix}. \tag{6}$$

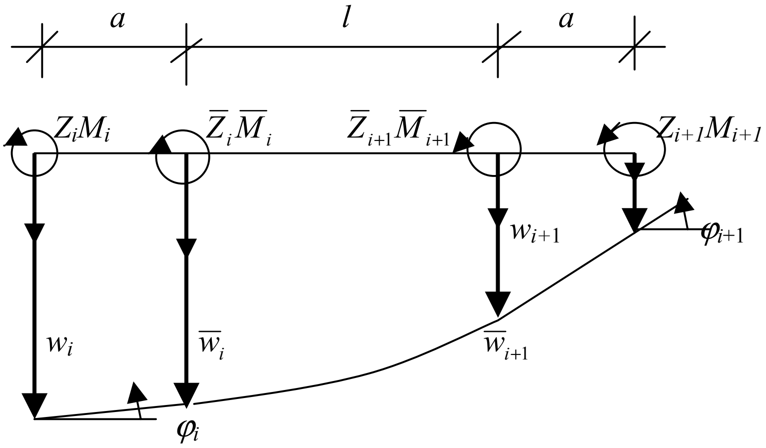

Fig. 4. Spine deformation is linear in the vertebrae parts and curve-linear in the inter-vertebrae disc part.

Let the boundary forces Z_i, M_i, Z_{i+1}, M_{i+1} and kinematic unknowns w_i, φ_I, w_{i+1}, φ_{I+1} be transformed from vertebrae centres to values $\overline{Z}_i, \overline{M}_i, \overline{Z}_{i+1}, \overline{M}_{i+1}, \overline{w}_i, \overline{\varphi}_i, \overline{w}_{i+1}, \overline{\varphi}_{i+1}$ at disc boundary points (see fig. 4). As there is no deformation between the vertebrae centre and the inter-vertebrae disc boundary, the central spinal line is straight in this part, the spine movement w has a linear course in the part of length a, and the torsion moment M_x and turning φ, φ_x are invariable.

$$\overline{w}_i = w_i - \overline{\varphi}_i a, \quad \overline{w}_{i+1} = w_{i+1} + \overline{\varphi}_{i+1} a, \quad \overline{\varphi}_i = \varphi_i, \quad \overline{\varphi}_{i+1} = \varphi_{i+1}, \tag{7}$$

$$\overline{M}_i = M_i + Z_i a, \quad \overline{M}_{i+1} = M_{i+1} + Z_{i+1} a, \quad \overline{Z}_i = Z_i, \quad \overline{Z}_{i+1} = Z_{i+1}. \tag{8}$$

Let us put (7), (8) to (5)

$$R_2 + \begin{Bmatrix} 0 \\ aZ_i \\ 0 \\ -aZ_{i+1} \end{Bmatrix} = \overline{K}^2 \left(r_2 + \begin{Bmatrix} -a\varphi_i \\ 0 \\ a\varphi_{i+1} \\ 0 \end{Bmatrix} \right). \tag{9}$$

The formula (9) can be written

$$R_2 = K^2 r_2 , \tag{10}$$

where K^2 is the stiffness matrix for vertebrae centres

$$K^2 = \begin{bmatrix} \frac{6k}{l^2} & -\frac{3k}{l}\left(\frac{2a}{l}+1\right) & -\frac{6k}{l^2} & -\frac{3k}{l}\left(\frac{2a}{l}+1\right) \\ -\frac{3k}{l}\left(\frac{2a}{l}+1\right) & k\left[2+\frac{3a}{l}\left(\frac{2a}{l}+1\right)\right] & \frac{3k}{l}\left(\frac{2a}{l}+1\right) & k\left[1+\frac{3a}{l}\left(\frac{2a}{l}+1\right)\right] \\ -\frac{6k}{l^2} & \frac{3k}{l}\left(\frac{2a}{l}+1\right) & \frac{6k}{l^2} & \frac{3k}{l}\left(\frac{2a}{l}+1\right) \\ -\frac{3k}{l}\left(\frac{2a}{l}+1\right) & k\left[2+\frac{3a}{l}\left(\frac{2a}{l}+1\right)\right] & \frac{3k}{l}\left(\frac{2a}{l}+1\right) & k\left[2+\frac{3a}{l}\left(\frac{2a}{l}+1\right)\right] \end{bmatrix}. \quad (11)$$

The analogical formulas are valid for y axis direction.

3.2 Pressed Soft Tissue (Elastic Ground)

The pressed soft tissue of a child trunk round the spine is considered as an elastic ground according to [1] pp. 86 – 113 and the final formulas will be used here. The width of the ground is considered constant. Let us calculate the parameters

$$C_1 = \frac{E_P}{h}, C_2 = \frac{E_P h}{6},$$

$$C_1^* = C_1 + \frac{1}{b}\sqrt{C_1 C_2}, C_2^* = C_2 + \frac{1}{2b}\sqrt{\frac{C_2^3}{C_1}},$$

$$C_3^* = \frac{1}{3}C_1 b^2 + C_2 + b\sqrt{C_1 C_2}, C_4^* = \frac{1}{3}C_2 b^2 + \frac{b}{2}\sqrt{\frac{C_2^3}{C_1}},$$

where E_P , h, b are modulus of elasticity, thickness and width of pressed soft tissue. The torsion stiffness sub-matrix is:

$$K^1 = \frac{bl}{3}C_3^*\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} + \frac{2b}{l}C_4^*\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}. \quad (12)$$

The beam stiffness sub matrix is:

$$K^2 = 2blC_1^*\begin{bmatrix} \frac{13}{25} & -\frac{11l}{210} & \frac{9}{70} & \frac{13l}{420} \\ -\frac{11l}{210} & \frac{l^2}{105} & -\frac{13l}{420} & -\frac{l^2}{140} \\ \frac{9}{70} & -\frac{13l}{420} & \frac{13}{35} & \frac{11l}{210} \\ \frac{13l}{420} & -\frac{l^2}{140} & \frac{11l}{210} & \frac{l^2}{105} \end{bmatrix} + \frac{2bC_2^*}{l}\begin{bmatrix} \frac{6}{5} & -\frac{l}{10} & -\frac{6}{5} & -\frac{l}{10} \\ -\frac{l}{10} & \frac{2l^2}{15} & \frac{l}{10} & -\frac{l^2}{30} \\ -\frac{6}{5} & \frac{l}{10} & \frac{6}{5} & \frac{l}{10} \\ -\frac{l}{10} & -\frac{l^2}{30} & \frac{l}{10} & \frac{2l^2}{15} \end{bmatrix}. \quad (13)$$

4 Spine Loading

The brace pushes the trunk in the place, where the plaster positive form of the child trunk has been deepened; it means that the trunk surface (soft tissue surface) has the non-zero prescribed displacements in these places. Let us suppose that the prescribed displacement acts for a lying patient from the above and the z-axis direction is from below. The compression of the soft tissue part up the spine is $w_0 - w$ and below it is w, where w is a spine displacement and w_0 is a prescribed trunk surface displacement. Let the matrixes K_{above}, K_{below} be calculated according to formulas (12) for the trunk part above and below the spine. The potential energy of the soft tissue part is

$$E_p = r^T\,[K_{above}\,(r_0 - r) + K_{\text{below}}\,r] = r^T\,[K_{\text{above}}\,r_0 + (K_{\text{below}} - K_{\text{above}})\,r.$$

The term $K_{\text{above}}r_0$ can be calculated and its negative form can be considered as a load vector (the right side of linear algebraic equations of the finite element method). In this way, the potential energy can be considered in compressed parts of soft tissue only; it means that the terms $K_{above}(r_0 - r)$ and/or $K_{below}\ r$ are considered only if they are positive. An iteration calculation is necessary for the correct results; it means that the load vector is calculated for the compressed soft tissue part above and/or below the spine according to the results from the last iteration step.

The oblique load will be searched. Let y,z be coordinates of the point of the center, where the positive plaster form was deepened and let Δ be the depth of how the plaster positive form has been deepened in perpendicular direction to the child trunk surface. Now, Δ is a prescribed trunk surface displacement and y,z its coordinates (positive displacement is in direction from the trunk surface to the spine). Let us consider that the trunk transversal cross-section has a half elliptic form with radiuses a, b for $z > 0$ and $a, \overline{b}$ for z < 0. The following formulas can be written for the ellipse

$$z = b\sqrt{1 - \frac{y^2}{a^2}} \tag{13}$$

If formula (13) is derived, angle φ of the tangent with axis y can be calculated; the negative value of angle φ is the angle of the normal with z axis.

$$tg\varphi = z' = -\frac{by}{a\sqrt{a^2 - y^2}}$$

The prescribed surface displacements v_0, w_0 in y,z directions are

$$v_0 = -\Delta \sin\varphi, \quad w_0 = \Delta \cos\varphi.$$

The problem can be solved in the plane x, y or x, z with prescribed displacements v_0 or w_0 or more correctly as a space problem with a space spine and soft tissue elements. The stiffness matrix for the space spine element can be considered in the same way as the formulas (4), (5) and (11) but the matrix K^2 (see (11)) has elements for the direction of axis y, too. As the vertebrae have no deformations, the kinematics variables at the vertebrae surface can be calculated from kinematic variables of vertebrae centres of gravitation (see (3)). The normal and tangential stresses on the boundary between a vertebra and an inter-vertebrae disc are then calculated from the resulting joint forces and moments. The normal force of the x-axis load has to be respected in the normal stress calculation, too, and the shear and torsion influence should be respected in the tangent stress calculation.

The parameters and calculation algorithm are verified with values observed in the X-ray of a child with and without the brace, it means that the calculated function values y, z and $y+v$, $z+w$ and their extremes are compared with the patient's X-ray..

5 Conclusion

If the brace is removed from the child trunk after some time of application, then the spine does not return to its previous position, but the pathologic spine form is partly corrected. Many child patients have been observed within this project and the dependence between the spinal curve correction and the spine stress state and the time interval of the brace application are studied. The theoretical conclusions about the spine remodelling are searched. The computer simulation model and its parameters are verified to ensure that the behaviour of the model is the same as the child treatment course. Since the treatment takes a long time, the theoretical conclusion can be determined after a sufficient number of verifications between the observed treatment courses and their computer simulations.

Acknowledgements

The research is supported by a grant of the Czech Grant Agency No. 106/00/0006 “Functional Adaptation and Pathobiomechanics Limb and Axial Skeleton under Force Effects“ and it is conducted in cooperation with orthopedist and pediatrician MUDr. Ivo Mařík, CSc. (“Center for Defects of Locomotor Apparatus”, Olšanská 7, 130 00 Prague 3), who has cured the patients, and Ing. Pavel Černý (“Orthotic Center”, Truhlařská 8, 110 00 Prague 1), who has made special braces and measurement instruments.

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