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COMPUTER SUPPORT TREATMENT OF SCOLIOSIS

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Summary: *The children scoliosis can be treated by a corrective brace. The computer program of a spine stress state and spinal deformation under the brace effects was composed and verified by real scoliosis treatment course. The brace is worked in this way: the first is made a negative and then the positive plaster form of the child trunk. The orthotic according to his and orthopaedist experiences deeps the plaster positive form at the places where the brace has to push on the child trunk. The plastic form is then made according to this plaster form. The computer algorithm of stress state calculation is based on the finite element method. The spine is considered as stiff at the vertebrae and elastic at the inter-vertebrae discs. The spine is solved as beam on an elastic base – the soft tissue of the trunk. It is determined the stiffness matrix of spine elements (spinal element is from the vertebra centre to neighbour vertebra centre) and the potential energy of elastic base influence. The trunk surface displacement is given by brace form and the prescribed displacements are used as system load. The brace pushes on soft tissue of trunk as small shoe principle. The computer program uses two algorithms: the first one has as input trunk surface displacements and as output spine stress and deformation state, the second algorithm has as input the spine deformation, measured as a difference between the X-rays of spine without and with brace and as the outputs and need trunk surface displacements as load influence. The second algorithm is better for clinic praxis. If the brace is applied for a long time the part spine deformation is corrected. The computer simulation of spine curvature remodelling is to of second part of article.*

1. Introduction

Corrective braces are used for the treatment of spine scoliosis of children (deformation of chest curve). The brace pushes on child trunk and after a long time using it corrects pathologic spine curve. The brace is worked at this manner: it is made a plaster negative and then a positive form of child trunk. The orthotic according to his and orthopaedist experience deeps the plaster positive form at the place where the brace has to push on the child trunk. The plastic brace is then made according to this plaster form. The brace after its application pushes at the places, where the form has been deepen (the small shoe principle). The brace force effect is result of orthopaedist experiences only. The paper shows algorithms and computer programs, which are able to determine the stress state at vertebras and inter-vertebrae discs for a concrete brace using. The remodelling of spine curvature

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depends on time and form of the brace application and it can be simulated on computer. The theoretic conclusions are verified with many treatment courses.

2. Spine stress and deformation state

2.1. Deformation of spine curve

The inertia moment is determined for an inter-vertebrae disc cross-section and lignums according to fig.1. The cross-section is divided to triangles and the third parts of areas are concentrated to the side centres.

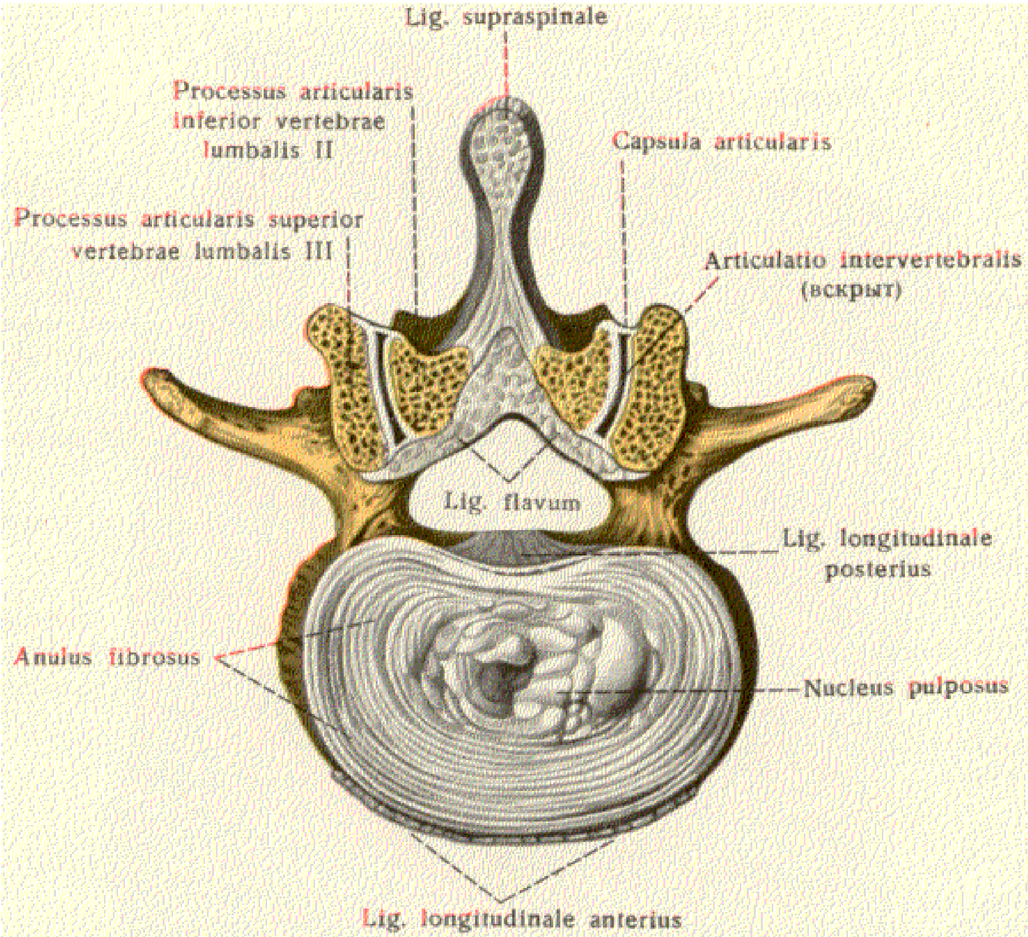

Fig. 1: Inter-vertebrae disc and ligaments.

The finite elements method (deformation variant according to Lagrange principle) is used for stress state solving. It is supposed that the vertebrates have no deformation. The potential energy is calculated for the inter-vertebrae discs volume and for the pressed soft The bright of soft tissue is for simplification considered constant (rectangle cross-section of trunk). Because it is no deformation between vertebrae centre and inter-vertebrae disc bounder, the central spine line is at this part straight. The displacements and turning at vertebrates are this kinematics' unknowns

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

where φ_x are turnings according to spine axis. The follow algorithm is valid for the frontal and sagital plane, the planes will not be indicated by the plane index.

Fig. 2. Patient with scoliosis, with corrective brace type Černý and her X-ray.

The stiffness matrix for the spine part between centres of neighbouring vertebrates is (torsion and beam influences)

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

The submatrixes will be determined separate for deformation of spine and for soft tissue.

2.2. Deformation of inter-vertebrae disc

The beam and torsion stiffness is $k = (2EI)/l$, $t = (GI_T)/l$, where E,I are the module of elasticity and the moment of inertia of a cross-section at the intervertebae disc and lignums place (see fig.1) and l is thick of disc. Torsion influence is
:

$$K^1 = \begin{bmatrix} t & -t \\ -t & t \end{bmatrix} \tag{3}$$

Let the bounder forces and kinematics' unknowns are transformed from vertebrae centre to disc bounder point. The spine axes movement has linear course at this part of length a (torsion moment M_x and turning φ, φ_x are invariable)

$$\overline{w}_i = w_i - \overline{\varphi}_i a\,,\quad \overline{w}_{i+1} = w_{i+1} + \overline{\varphi}_{i+1} a\,,\quad \overline{\varphi}_i = \varphi_i\,,\quad \overline{\varphi}_{i+1} = \varphi_{i+1} \tag{4}$$

$$\overline{M}_i = M_i + Z_i a\,,\quad \overline{M}_{i+1} = M_{i+1} + Z_{i+1} a\,,\quad \overline{Z}_i = Z_i\,,\quad \overline{Z}_{i+1} = Z_{i+1} \tag{5}$$

The beam stiffness matrix (see [2], p.99) for intervertebrae disc part was transformed to kinematics´ unknown at vertebrae centres according to formulas (4), (5)

$$K = \lfloor K_{i,j} \rfloor \tag{6}$$

where

$$K_{1,1} = K_{3,3} = -K_{1,3} = \frac{6k}{l^2}$$

$$K_{2,2} = K_{4,4} = K_{2,4} = k\left[2 + \frac{3a}{l}\left(\frac{2a}{l} + 1\right)\right]$$

$$K_{2,3} = K_{3,4} = -K_{1,2} = -K_{1,4} = \frac{3k}{l}\left(\frac{2a}{l} + 1\right)$$

$$K_{i,j} = K_{j,i}$$

The analogical formulas are valid for *y* axe direction.

2.3. Pressed soft tissue solved as an elastic grunt

The pressed soft tissue is considered as an elastic grunt according to [1] pp. 86 – 113, the final formulas will be used at this article. A bright of grunt is considered constant. Let us calculate the parameters (E_P , *h, b* are module of elasticity, thick and bright of pressed soft tissue)

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

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

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

The torsion stiffness submatrix is:

$$K^1 = \frac{bl}{3}C_3^*\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} + \frac{2b}{l}C_4^*\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{7}$$

The beam stiffness submatrix is:

$$K^2 = K_1^2 + K_2^2 \tag{8}$$

where

$$K_1^2 = 2blC_1^* \begin{bmatrix} \frac{13}{25} & -\frac{11l}{210} & \frac{9}{70} & \frac{13l}{420} \\ -\frac{11l}{210} & \frac{l^2}{105} & -\frac{13l}{420} & -\frac{l^2}{140} \\ \frac{9}{70} & -\frac{13l}{420} & \frac{13}{35} & \frac{11l}{210} \\ \frac{13l}{420} & -\frac{l^2}{140} & \frac{11l}{210} & \frac{l^2}{105} \end{bmatrix}$$

$$K_2^2 = \frac{2bC_2^*}{l} \begin{bmatrix} \frac{6}{5} & -\frac{l}{10} & -\frac{6}{5} & -\frac{l}{10} \\ -\frac{l}{10} & \frac{2l^2}{15} & \frac{l}{10} & -\frac{l^2}{30} \\ -\frac{6}{5} & \frac{l}{10} & \frac{6}{5} & \frac{l}{10} \\ -\frac{l}{10} & -\frac{l^2}{30} & \frac{l}{10} & \frac{2l^2}{15} \end{bmatrix}$$

2.4. Loading of spine

The brace pushes at a child trunk at the place, where the plaster positive form has been deepen; it means that the trunk surface (soft tissue) has at these places the non-zero prescribed displacements. The prescribed displacement is supposed above for lying patient. The compression of the soft tissue part up the spine is $w_0 - w$ and below it is w (for $w_0 > w > 0$), 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 (8) for trunk part above and below the spine. The variation of potential energy of soft tissue part is

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

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 the way, the potential energy can be considered in compress parts of soft tissue only; it means that the term $K_{above}(r_0 - r)$ is considered for $w_0 > w$, $w_0 > 0$ and/or $K_{\text{below}}(r_0 - r)$ for $w_0 < w$, $w_0 < 0$ and analogous $K_{\text{below}} r$ for $w > 0$ and/or $K_{above} r$ for $w < 0$. An iteration calculation is necessary for the correct results; it means that the load vector is calculated for soft tissue part above or below the spine according to the results from the last iteration step.

The normal and tangential stresses on the bounder between a vertebrae and an inter-vertebrae disc are then calculated from the result joint forces and moments. The axis load has to be respected at normal stress calculation too and the shear and torsion influence at the tangent stress calculation.

3. Computer simulation of scoliosis treatment

Let us suppose that the spine curve correction is percentage constant at a time unit. If it is known a spinal curve y at time t ,it is the spinal curve $y(t + step) = k\, y(t)$. If is $y(0) = y_0$, then it is

$$y(t) = k^t y_0 \qquad (9)$$

It is supposed that the curves y(t) and y_0 have the roughly same form and k is around constant. If a X-ray in time t_1 is made, it means that $y(t_1)$ is known, then the parameter k can be calculated from

$$k = \left(\frac{y(0)}{y(t_1)} \right) \text{ or } k = \left(\frac{dy(0)/dx}{dy(t_1)/dx} \right)$$

The second formula is more useful because the extreme values of spinal axis angle can be measure easier. The parameter k can be determined with help statistical observation. The value of parameter k depends on

- type of spinal curve defect according to King and Moe,
- spine stress state,
- time of daily using,
- total time of treatment,
- age and sex.

The table 1 shows the results of treatment according to spinal curve type. The colons marked 'Th' or/and 'L' are thoracic and lumbar spine parts. The 1st colons are for Chêneau and 2nd ones for Černy types of brace. The percentage corrections of spinal defect (spinal axis rotation angles) are present the first and the number of cured patients at the parenthesis.

Tab. 1. The result of treatment.

King - Moe	Th % (No.)	L % (No.)
I	52(87) / 59(47)	60(87) / 51(47)
II	39(32) / 35(19)	53(32) / 54(19)
III	48(46) / 48(58)	47(46) / 49(58)
IV	62(10) / 47(5)	47(10) / 47(5)
V	11(2) / 30(2)	13(2) / 60(2)
CHÊNEAU / CERNY	49(177) / 49(131)	56(177) / 49(131)

4. Discussion

The limitation of bracing is generally due to the severity of scoliosis, biochemical and anatomical abnormalities of the skeleton (secondary osteoporosis and deformities of spine and thorax, e.g. in osteogenesis imperfecta, Marfan syndrome, Ehlers-Danlos syndrome, neurofibromatosis, etc.) and/or associated diseases of other systems, the type of brace and technical restriction of brace effectiveness (it can be improved).

The time factors of orthotic treatment play considerable task (start of bracing, night-time, part-time and full-time regime, end of bracing). Comprehensive treatment (rehabilitation, orthotic fitting, treatment of joint disease, etc.) contains close cooperation and motivation of patients and their parents.

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-vertebral 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 can measure 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. The long-term following of the group of patients is going on till adulthood.

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

5. Conclusion

The aim of this research study is the evaluation of correction attained by the classical spinal Chêneau-brace and new developed dynamic corrective spinal brace according to Černý (patent No.: 281 800 CZ). The Chêneau-brace is suitable and indicated for all types of scoliosis curves. We recommend it for the spinal curves type King I, II, and IV. The Černý brace is suitable for flexible curves especially for the spinal curves of type King II, III a V. It is not indicated for the King type IV. The advantage of this brace is a possibility of inclination to both sides with favourable effect. The average effectiveness of the Chêneau and Černý brace is approximately the same. Prompt diagnosis and start of bracing with comprehensive treatment is a presumption of the best results. There are still questions of bracing in children with Cobb angle below 20 degrees, start of bracing after sex maturation and around intermittent bracing in adulthood. Bracing in thoracic idiopathic scoliosis with marked lordosis in the thoracic spine has poor prognosis.

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.

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