COMPUTER AID CHILDREN SCOLIOSIS TREATMENT

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Abstract: Orthopaedists in the Czech Republic use corrective braces of type Cheneau or Cerny for conservative treatment of non skeletal scoliosis. The brace has force effects on a child spine and if it is used for enough long time the spine defect is corrected. The brace is made individually for each patient in this way: first, the negative plaster form of a child trunk and then the positive plaster form are made. The positive plaster form is deepened in the places where brace has to push on the patient trunk. The laminate brace made according to this plaster form pushes the child trunk like a tight shoe principle. The paper shows computer algorithm for solving of the stress state in vertebrae and inter-vertebrae discs and the spinal curve correction under brace force effects for a concrete child patient. The stress state at the spine and spine deformation correction are solved by the finite element method as a beam (spine) on an elastic ground (soft tissue). There are used two algorithms. The 1st algorithm solves the spine stress state and deformation under brace force effect given by displacements of trunk surface. The 2nd algorithm has as input the spinal curves of a patient and a ideal spinal curve. The output is trunk surface displacements which is equal to the optimal brace form. The calculation algorithm and parameters ware verified with treatment courses. The trunk surface load was checked by sensor plates which ware put into braces to measure the load values between the brace and the child trunk surface. The 2nd part of paper shows computer aid prognosis of the treatment course for concrete patient.

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.

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 at the places where the form has been deepened (the tight shoe principle).

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

If a 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 a computer aid design of brace form and calculation algorithms for vertebrae and inter-vertebrae discs stress and deformation calculation for the concrete brace applications. The theoretical conclusions ware made according to many observations of treatment courses. The remodelling of the spine pathologic curve depends on the type of spinal defect, 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 prediction 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

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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.

Materials and Methods

The spinal curve is stored in the computer as the following 3 functions

$$y = y(x),\ z = z(x),\ \varphi = \varphi(x), \qquad (1)$$

where x is axis linking spine end at X-ray, y, z are spine positions at frontal resp. sagital planes and φ is the turning angle according to the x-axis. The extreme values of y, z are measured on the X-ray (the extremes of the yellow curve in the left X-ray in fig.2) and the spinal curves (1) are constructed as polynomial approximation between extremes. The method is applied for the frontal and sagital planes and for torsion angles, too. The measured method for torsion angles was published at [7].

The spine stress and deformation state is calculated with help finite element method (FEM). The FEM supposes that inter-vertebrae discs are elastic and vertebrae are stiff relative to discs. The potential energy for the FEM is calculated for inter-vertebrae parts of spine only and that's why 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 and moments of inertia are calculated as sum of the triangle moments.

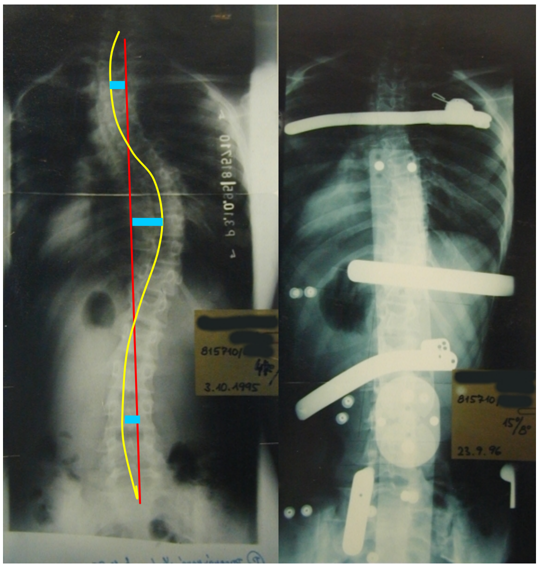

Figure 2: The frontal X-ray of the patient from fig.1 without and with the corrective brace.

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

$$K = \begin{bmatrix} K^1 & 0 \\ 0 & K^2 \end{bmatrix} \qquad (2)$$

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

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

$$K^1 = \begin{bmatrix} t & -t \\ -t & t \end{bmatrix} \qquad (3)$$

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)

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

$$\overline{\varphi}_i = \varphi_i\ ,\quad \overline{\varphi}_{i+1} = \varphi_{i+1}\ , \qquad (4)$$

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

The beam stiffness matrix (see [2], p.99) for inter-vertebrae disc part was transformed to kinematics unknowns at vertebrae centers according to formulas (4), (5)

$$K = \left[K_{i,j}\right] \qquad (6)$$

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.

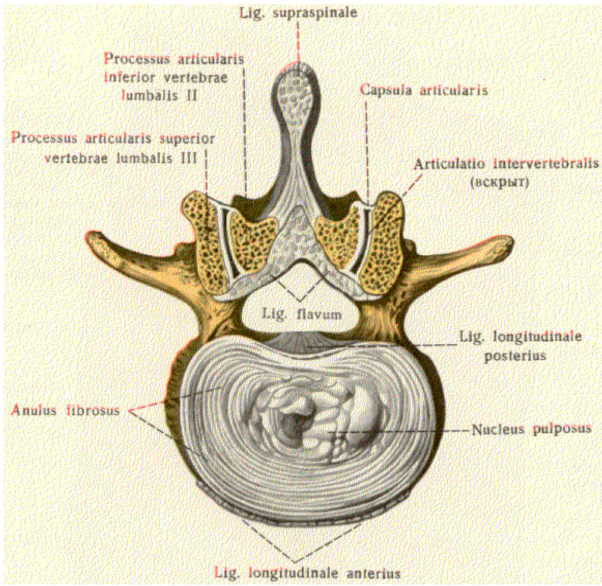

Figure 3: Inter-vertebrae disc and lignums.

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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:

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

The beam stiffness submatrix is:

$$K^2 = K_1^2 + K_2^2 \qquad (8)$$

where

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

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

The brace pushes 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 w_0. The compression of the soft tissue part up the spine of laying patient is $w_{0,above} - w$ and below it is $w + w_{0,below}$, where w is a spine displacement and w_0 are prescribed trunk surface displacement above and below of the patient trunk. The functions w, w_0 are determined by parameters of joint deformations r, r_0. Let the matrixes K_{above}, K_{below} be calculated according to formulas (8). The variation of potential energy of soft tissue part is

$$\delta E_p = \delta r^{\mathrm{T}} [K_{above}(r_{0,above} - r) \text{ and/or } K_{\mathrm{below}}(r + r_{0,below})] =$$
$$= \delta r^{\mathrm{T}} [K_{below} r_{0,\mathrm{below}} - K_{\mathrm{above}} r_{0,above} + (K_{\mathrm{below}} + K_{\mathrm{above}}) r]$$

The term $K_{below} r_{0,\mathrm{below}} - K_{\mathrm{above}} r_{0,above}$ 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 terms K_{above} $(r_{0,above} - r)$ and/or K_{below} $(r + r_{0,below})$ are considered if they are positive only. An iteration calculation is necessary for the correct results; it means that the load vector is calculated for soft tissue part above and/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.

The second aim of paper is prognosis of treatment course.

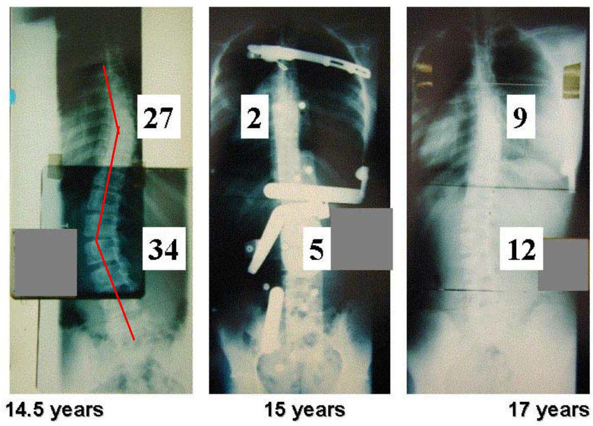

Figure 4: The frontal X-ray of the patient without and with the corrective brace, thorastic and lumbar angles.

A spinal defect is judged according to thoracic and lumbar angles (tangent angles at point with zero curvatures) see fig. 4. Let us suppose that the angles correction (angles increasing) is percentage constant at a time unit and it is convergent to the final value a_f. The treatment course prognosis is determined by

$$\alpha(t) = \alpha_f + ak^t \qquad (9)$$

where a is final correction (a > 0) or increasing of defect (a < 0), t is time and $k < 0$ is parameter depending on speed of treatment. The prognosis algorithm depends on number of X-ray controls. Let us show algorithms for number of X-ray controls 1, 2, n>3.

1. If we have spinal angles measured from one X-ray only at beginning of treatment then it can be judged on treatment course prognosis only according to results of previous cases. The treatment course depends on type of defect according to King, size of defect, age, treatment intensity and sex.

2. If we have spinal angles measured from two X-rays at time points $t_1 = 0$ and $t_2 > 0$, it can be judged on a final thoracic and/or lumbar angles a_f, for example

$$\alpha_f = \alpha(0) - (\alpha(0) - \alpha(t_2))2$$

From (9) can be calculate for $t = 0$

$$\alpha = \alpha_0 - \alpha_f$$

and for $t = t_2$

$$k = \left(\frac{\alpha(t_2) - \alpha_f}{a}\right)^{\frac{1}{t}}$$

3. If we have spinal angles measured from n X-rays at time points $t_1, t_2, \dots, t_n$, the parameters α_f, w and k can be solved to be the quadratic error minimal. The quadratic error is

$$\varepsilon = \sum_{1}^{n} \left[\alpha_i - \alpha(t_i)\right]^2 \qquad (10)$$

where α_i are measured values and $\alpha(t_i)$ are values calculated from (9). The conditions of extreme are

$$\frac{\delta\varepsilon}{\delta\alpha_f} \equiv \sum_{i=1}^{n} (2\alpha_f - 2\alpha_i + 2ab_i) = 0 \qquad (11)$$

$$\frac{\delta\varepsilon}{\delta w} \equiv \sum_{i=1}^{n} (2ab_i^2 - 2\alpha_i b_i + 2\alpha_f b_i) = 0 \qquad (12)$$

from (11) and (12) flows

$$\alpha_f = \alpha_c - ab_c \qquad (13)$$

$$a = \frac{\sum_{i=1}^{n} (\alpha_i - \alpha_c) b_i}{\sum_{i=1}^{n} (b_i - b_c) b_i} \qquad (14)$$

where is designated

$$b_i = k^{t_i}\ (i = 1,2,\dots,n), \alpha_c = \frac{\sum_{i=1}^{n} \alpha_i}{n}, b_c = \frac{\sum_{i=1}^{n} b_i}{n} \qquad (15)$$

If it is given k then b_i, α_c, b_c can be calculated from (15), a from (14), α_f from (13) and finally quadratic error ε from (9) and (10). The parameter k will be searched to be error ε minimal according to follow algorithm (k_0 is result from algorithm for two X-ray controls):

1. $k_1 = k_0$, *step* = 0,1 k$_1$, $\alpha_1 = \alpha(k_1)$, B = *true*
2. $k_2 = k_1 +$ *step*, $\alpha_2 = \alpha(k_2)$
3. if $\varepsilon_2 < \varepsilon_1$ then ($k_1 = k_2$, $\varepsilon_1 = \varepsilon_2$ and continue from 2)
4. if B then (*step* = -*step*, B = *false* and continue from 2)
5. *step* = *step*/2, B = *true*
6. if *step* > $step_{min}$ then continue from 2

The result of algorithm is

$$k = (k_1 + k_2)/2$$

Now the treatment course can be provided according to formula (9).

Results

The two computer algorithms of spine stress state by FEM can be used. The 1st one has as input brace form (trunk surface prescribed displacements) and as output spinal curve correction. The 2nd one has as input value spinal curve (spinal defect) correction.

Discussion

The spinal curve of patient can be measured on X-ray. If the spinal correction (deformation w) as difference between measured curve and ideal curve is put to 2nd algorithm of stress state calculation then the trunk surface displacements w_0 can be interpreted as ideal brace form and the 2nd algorithm can be used as computer aid design.

The treatment course prognosis is programmed on computer and can be used at clinical praxis

Conclusion

The algorithms ware verified with data base of cured patients at Ambulant Centre for Defects of Locomotor Aparatus (Ivo A. Mařík, M.D., Ph.D., F.A.B.I.) and ORTOTIKA a.s. (Eng. Pavel Černý).

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