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FORCE PRESCRIBING BRACE FOR CHILD SCOLIOSIS TREATMENT

J. Čulík[*]

Summary: *The children scoliosis is conservative treated by corrective braces. The brace is made individually for each patient. The article shows the new type of corrective brace with regulated force effect pat. n. 20022-3530CZ. The first is made the negative and then the positive form of children trunk. The final plastic brace is made according to the positive form. The brace consist of 2 or 3 parts connected by joints and on the appositive sides by telescopes with adjusted forces. This article describes the brace which has 2 parts. It can be used for spine defects at form letter 'C' (spinal curve has only one extreme). The first is shown the algorithm for calculation of the stress state at spine and spine correction for given brace force effect. The second part of article shows the calculation of an optimal values of telescope forces.*

1. Introduction

The children scoliosis is conservative treated with help corrective braces. The corrective brace is at Czech rep. individual made according to child trunk. The first is made negative and then the positive plaster form of child trunk and according to this positive plaster form is made plastic brace. The braces are made as stiff shells from plastic. The braces Cheneau type and/or Cerny type (pat. 281800CZ) are mostly applied at Czech Republic. These brace types good corrects spine curve deformities at frontal and sagital planes but the correction cannot be regulated. The corrective brace which are used at day time can be used at night too. But the night application of brace prepared for day time is not optimal at night because the child body at horizontal position has the different parameters. The ideal night brace is about several centimeters longer and more slender then the brace for the whole day using.

The new developed brace pat. 20022-3530CZ with regulated force effect is more effective mainly for night using.

2. Methods

The new developed brace with regulated force effect (see fig. 1) consists from 2 or 3 parts stiff plastic shells which are mutual connected by pairs of ball joints and at appositive sides by

[*] Prof. Ing. Jan Čulík, DrSc.: Czech Technical University of Prague, Faculty of Biomedical Engineering, Sítná 3105, 272 01 Kladno, tel.: +420 312 608 2008, fax: +420 312 608 204, e-mail: culik@fbmi.cvut.cz

telescopes. The special telescopes were developed which make possible to adjust prescribed force values (see fig. 2). The stiff joints can be used for small children. The force has moment affect to joint and the moment has an affect on child trunk witch instrumentality brace. The moments operate at frontal place and corrected spine defect at this plane.

Fig. 1: Brace with regulated force effect.

Fig 2: Telescope with regulated force.

The calculation algorithm used the presumptions:

1. The brace parts have deformations but the deformations are not study. The course and values of load between the brace and patient trunk surface were measured on concrete

patients with help sensors. The equations conditions are written for telescope forces (external forces) and designed course of trunk reaction (inner forces).

2. The vertebra deformation is insignificant to deformation of inter-vertebrae parts therefore the vertebrae are considered stiff.
3. Inter-vertebrae parts are considered elastic.
4. The load from brace to trunk is perpendicular to spine at frontal plane only.
5. The moments operate at frontal place and corrected spine defect at this plane and the brace is appropriated for defect at frontal plane only.

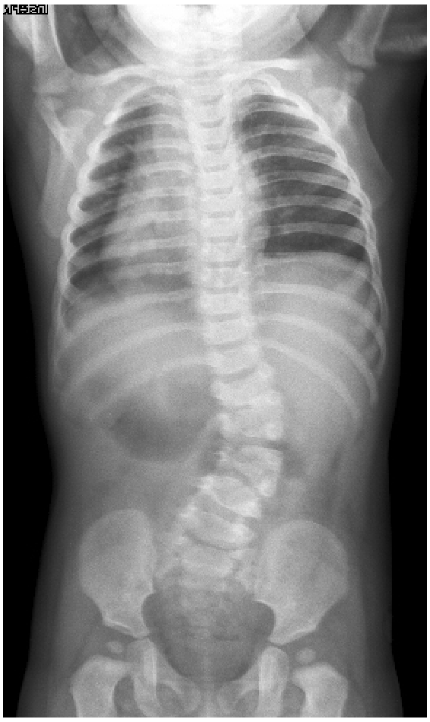

Fig. 3: RTG of patient with scoliosis.

3. Results

3.1. Spine defect correction

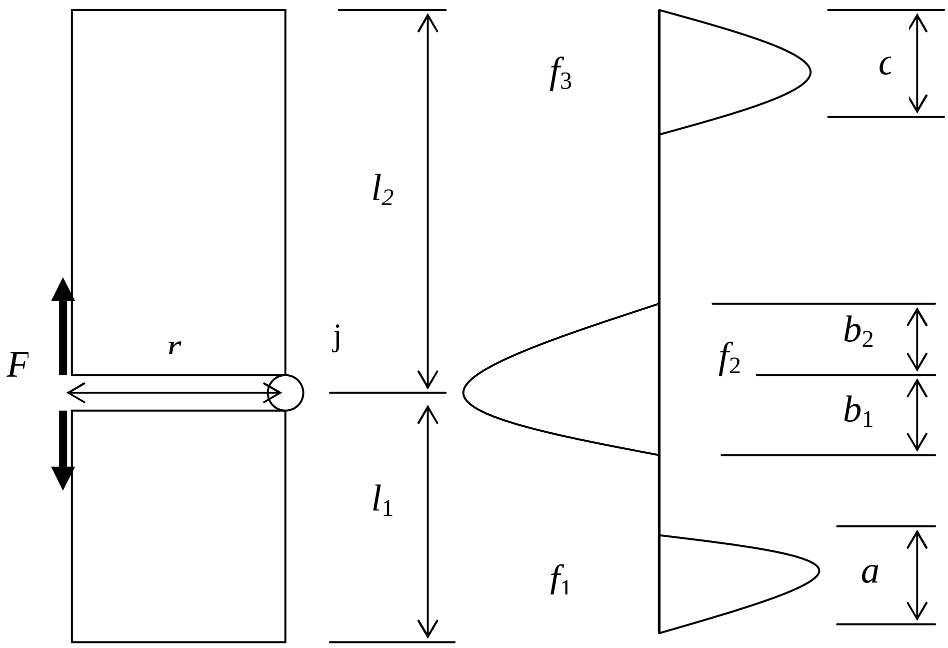

Fig. 3: Schema of brace and its force effect to patient trunk.

The schema of brace is at fig. 3. The brace consists from two parts: the lumbar part length l_1 and a thoracic part length l_2. The brace parts are connected by joint j and telescope with adjustable force F at appositive side. The brace turns a patient trunk with moment

$$M = F.r. \tag{1}$$

The moment effect is carried to a patient trunk. The patient trunk is loaded partly by continuous parabolic loads. The parabolic load with maximal value f_2 is under the brace joint. This parabolic load is unsymmetrical with bright b_1 on lumbar part and b_2 on thoracic part. The parabolic load are too on lumbar brace end with bright a and maximal value f_1 and on thoracic part end with bright c and maximal value f_3. The values f_1, f_2, f_3 were determined from moment equilibrium conditions of external force F and parabolic loads to joint j. The spine is solved as a beam and it is considered stiff at vertebra parts and elastic at the inter-vertebrae parts.

The moment equilibrium conditions to point j are

$$\frac{2}{3}af_1\left(l_1-\frac{a}{2}\right)-\frac{2}{3}b_1f_2\frac{3}{8}b_1=Fr\,, \tag{2}$$

$$\frac{2}{3}cf_3\left(l_2-\frac{c}{2}\right)-\frac{2}{3}b_2f_2\frac{3}{8}b_2=Fr\,. \tag{3}$$

From (2), (3)

$$f_1=\frac{3Fr}{2a\left(l_1-\frac{a}{2}\right)}+\frac{3b_1^2f_2}{8a\left(l_1-\frac{a}{2}\right)}, \tag{4}$$

$$f_3=\frac{3Fr}{2c\left(l_2-\frac{c}{2}\right)}+\frac{3b_1^2f_2}{8a\left(l_2-\frac{c}{2}\right)}. \tag{5}$$

The horizontal equilibrium condition is

$$\frac{2}{3}af_1+\frac{2}{3}cf_3-\frac{2}{3}(b_1+b_2)f_2=0\,. \tag{6}$$

From (4), (5) and (6) is

$$f_2=Fr\frac{\dfrac{1}{\left(l_1-\frac{a}{2}\right)}+\dfrac{1}{\left(l_3-\frac{c}{2}\right)}}{\dfrac{2}{3}(b_1+b_2)-\dfrac{b_1^2}{4\left(l_1-\frac{a}{2}\right)}-\dfrac{b_2^2}{4\left(l_2-\frac{c}{2}\right)}}. \tag{7}$$

The ratio of dimension l_1, l_2, a, b_1, b_2, c were estimated according to measurements at applied braces:

$$l_2 = 2l_1,\ a = b_1 = 0.2\ l_1,\ c = b_2 = 0.2\ l_1. \tag{8}$$

The loading coefficients for the measured dimensions are

$$f_1=8.878504674Fr/l_1^2\,, \tag{10}$$

$$f_2=6.54205609Fr/l_1^2\,, \tag{11}$$

$$f_3 = 4.205607477 Fr / l_1^2 . \tag{13}$$

The spine will be solved as beam loaded partly by parabolic loads. The spine is considered stiff at vertebrae parts and elastic at inter/vertebrae parts.

The differential equations for the spinal bend curve is

$$EIw'''' = f. \tag{14}$$

The spine consists of vertebrae and soft inter-vertebrae tissues – inter-vertebrae discs and ligaments. The vertebrae deformation will be neglected ($EI \to \infty$). The moment of inertia and areas of inter-vertebrae cross sections can be determined as sum of triangles. The values need not be determined for each patient but they can be calculated for one patient and for concrete patient recalculated according to a scale. The patient with lumbar vertebra width 5 cm at frontal plane has area of horizontal cross section of inter-vertebrae disc and ligament $A = 17.9$ cm^2 and moment of inertia $I = 26.0044$ cm^4 (axis at medial direction). The patient with vertebra width a has

$$A = 17.9a^2/25, \; I = 26.0044a^4/625 . \tag{15}$$

Each inter-vertebrae part can be considered correctly with different cross section characteristics A, I or less correctly and easier by a constant values of A, I for all inter-vertebrae parts. The influence of the less thoracic vertebrae diameter is eliminated by bending resistance of ribs.

The differential equations for shear forces Q and bending moments M are

$$Q' = -f, \quad M' = Q . \tag{17}$$

The differential equation (14) will be solved step by step at vertebrae and inter-vertebraes parts. They will be labeled by index '0' values at origin of solved intervals and the coordinate ξ is distance from the interval origin.

The first will be solved unloaded spine parts. The bending moment M and transverse force Q are

$$Q = Q_0, M = M_0 + Q_0\xi , \tag{18}$$

where Q_0, M_0 are values at interval origin.

Now the loaded spine parts will be solved. The parabolic load (see fig. 3) is defined by function (positive direction is down)

$$f = -\frac{p}{l}\eta^2 + p\eta ,$$

where η is distance from origin of parabolic load, l is length of parabola and parameter p is

$$p = \frac{4f_i}{l} ,$$

where f_i is the maximum value at center of parabolic load.

The shear force Q and bending moment M below the parabolic load are

$$Q = Q_1 + \frac{p\eta^3}{3l} - \frac{p\eta^2}{2} , \tag{15}$$

$$M = M_1 + Q_1\eta + \frac{p\eta^4}{12l} - \frac{p\eta^3}{6}. \tag{16}$$

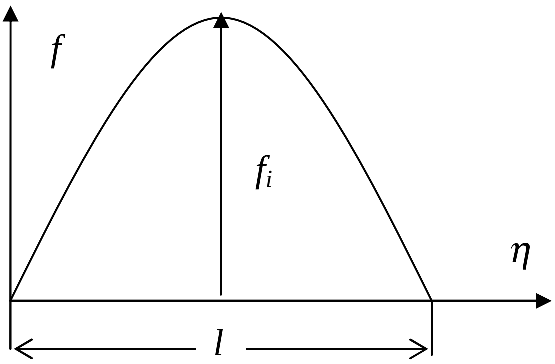

Fig. 4: Parabolic load of spine.

The movement w and turning φ are given by differential equations

$$w' = \varphi, \quad \varphi' = -\frac{M}{EI}(1+\varphi^2)^{\frac{3}{2}}. \tag{17}$$

The movement w and turning φ are at vertebra parts ($EI \to \infty$) are

$$\varphi = \varphi_0, \; w = w_0 + \varphi_0\xi \tag{18}$$

and at parts of inter-vertebrae discs are differential equations solved numerical. Matrix form of the differential equations (17) are

$$\mathbf{Y} = \begin{Bmatrix} \varphi \\ w \end{Bmatrix}, \quad \mathbf{Y}' = \mathbf{f}(x, \mathbf{Y}) = \begin{Bmatrix} \frac{M(x)}{EI}\left(1+\varphi^2(x)\right)^{\frac{3}{2}} \\ \varphi(x) \end{Bmatrix}$$

The solving by Runge-Kutta's method at interval $\langle x_0, x_0 + h\rangle$ is

$$\mathbf{K}_1 = \mathbf{f}\,(x_0, \mathbf{Y}_0),$$

$$\mathbf{K}_2 = \mathbf{f}(x_0 + \frac{h}{2}, \mathbf{Y}_0 + \frac{\mathbf{K}_1}{2}),$$

$$\mathbf{K}_3 = \mathbf{f}(x_0 + \frac{h}{2}, \mathbf{Y}_0 + \frac{\mathbf{K}_2}{2}),$$

$$\mathbf{K}_4 = \mathbf{f}(x_0 + h, \mathbf{Y}_0 + \mathbf{K}_3),$$

$$\mathbf{Y}(x_0 + h) = \mathbf{Y}(x_0) + \frac{h}{6}(\mathbf{K}_1 + 2\mathbf{K}_2 + 2\mathbf{K}_3 + \mathbf{K}_4).$$

The positive direction of used values (sign rule) is follow (directions according to fig.3): transversal force Q is positive upwards from the left side and downwards from the right, bending moment M is positive if the lower spine part is pulled, movement w is positive down and turning φ is positive at clockwise.

If the small deformation theory will be used, the displacement w and turning φ at parts of inter-vertebrae discs can be calculated according to formulas

$$\varphi = \varphi_0 - \frac{1}{EI}\left[M_1(\eta-\eta_1) + Q_1\frac{\eta^2-\eta_0^2}{2} + \frac{p(\eta^5-\eta_0^5)}{60l} - \frac{p(\eta^4-\eta_0^4)}{24}\right], \tag{19}$$

$$w = w_0 + \varphi_0\xi - \frac{1}{EI}\left[M_1\frac{(\eta^2-\eta_0^2)}{2} + Q_1\frac{(\eta^3-\eta_0^3)}{6} + \frac{p(\eta^6-\eta_0^6)}{360l} - \frac{p(\eta^5-\eta_0^5)}{120}\right], \tag{20}$$

where ξ is coordinate from interval origin and η from parabolic load origin. The values at interval origin is labeled by index ‘0’ and values at parabolic load origin is labeled by index ‘1’, η_0 is the distance of the parabolic load origin.

The height of vertebrae can be measured on the X-ray or judge from observed length of spine interval l and number of vertebrae n at this interval. The average thickness of inter-vertebrae discs is

$$a = \frac{l}{6(n-1)}.$$

The average height of vertebra is

$$h_{average} = \frac{l-(n-1)a}{n}.$$

The height of concrete vertebra is (the vertebrae are numbered at superior direction)

$$h_i = h_{average} + \frac{0{,}2h_{average}}{n-1}\left(\frac{n-1}{2} - i - 1\right).$$

The calculation starts with initial conditions $w_0 = 0$, $\varphi_0 = 0$, $M_0 = 0$, $Q_0 = 0$ and it is repeated at all vertebra and inter-vertebrae intervals. The results w_i, φ_i, M_i, Q_i at the ends of intervals are calculated according to previous formulas and they are used as initial conditions at the next intervals. The final value at last interval is w_f. Now we correct the initial condition φ_0 to be the final value $w_f = 0$.

$$\varphi_0 = -\frac{w_f}{l}. \tag{21}$$

The previous calculation can be repeated with new initial condition φ_0 or the values w_i, φ_i can be corrected in this way

$$w_{i,new} = w_i + \varphi_0 x, \quad \varphi_{i,new} = \varphi_i + \varphi_0, \tag{22}$$

where x is a distance from origin of the spine (first interval origin).

3.2. Computer help design

The brace shape, dimensions of its parts l_1, l_2, l_3, joint and telescope position, their mutual distance and load position are given by patient’s which are determined by the help of plaster positive form of patient’s trunk. The pathologic spinal curve is diagnosed according to X-ray. The task is to compile computer program for searching the telescope forces to determine the optimal spinal curve correction. The ideal spinal curve at frontal projection is in line. The ideal correction is pathologic spinal curve with opposite sign.

The positions and values of extremes of spinal curve are measured by X-ray. The spinal curve is approximated by polynomials between the extremes. The approximate polynomial for the 1st segment is

$$y = \frac{y_i}{l}\xi\left(2 - \frac{\xi}{l}\right), \tag{23}$$

for middle segment

$$y = y_{i-1} + \frac{(y_i - y_{i-1})\xi^2}{l^2}\left(3 - 2\frac{\xi}{l}\right) \tag{24}$$

and for last segment

$$y = y_{i-1}\left(1 - \frac{\xi^2}{l}\right) \tag{25}$$

where l length of segment, y_{i-1}, y_i are local extremes at left and right ends and ξ is local coordinate with origin on left end of segment. The ideal correction at all centers of vertebrae $w_{i,ideal}$ are values calculated from (19) to (21) with opposite sign.

The telescope forces F_1, F_2 will be searched to be quadratic error of ideal correction at the vertebra centers $w_{i,ideal}$ and calculated values w_i for forces F_1, F_2 minimum, it means to be minimal value

$$\varepsilon = \sum_{i=1}^{n}(w_i - w_{i,ideal})^2 \tag{26}$$

The minimum of error ε is search with help method of maximal slope, where partial derivation is calculated numerical with given *step.* The new estimate of telescope force is in direction of maximal slope at distance *step.* If the error ε is not smaller the half *step* will be used. The iteration calculation is finished if telescope force *step* is less than given value. The result error ε is not zero because the spinal curve correction has not the same form as pathologic spinal curve observed on RTG.

The follow calculation algorithm can be used:

1. F = initial approximation, "spine solving and calculation of ε_{old}", B = true, $step = F/10$.
2. **Cycle** i = 1 **to** 50.
3. $F_{old}=F$, $F=F+step$.
4. "solving of spine and calculation of error ε". $S=\varepsilon - \varepsilon_{old}$.
5. **if** $S_j > 0$ **and** B **then** ($S= -S$, $step= -step$, $F=F_{old}$, **go to** 4).
6. **if** $\left|\varepsilon - \varepsilon_{old}\right| < 0.1$ **then go to** 10.
7. **if** $\varepsilon > \varepsilon_{old}$ **then** ($step= step/2$, **if** $step < 0,01$ **then go to** 10 **else** $\varepsilon_{old} = \varepsilon$.
8. End of cycle i.

4. Conclusion

The problem of spine stress state and deformation was solved by beam theory and by finite element method (FEM) too. The first method demonstrates that article neglects the soft tissue compression, the algorithm is simple and enough precise. The solution by FEM was interpreted by computer too; the solving considers potential energy of inter-vertebrae parts and compressed trunk soft tissue and neglects skeleton bone deformation.

The presented algorithm was implemented on computer and the results were verified with cured patients.

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