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Original Article

Treatment of children scoliosis by corrective brace with regulated force effect

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Abstract

Rigid structural spine scoliosis of a child and even non progressive congenital scoliosis (e.g. isolated hemivertebra) can be treated by hypercorrective brace in full day regime. The article shows the new type of corrective brace with adjustable force effect. The brace consists of 3 stiff parts connected by joints and telescopes. The parts of brace are made from plastic according to plaster form of child trunk. The joints allow only mutual turning brace parts at frontal plane. The special telescopes were developed which operated with prescribed forces, it means the brace and trunk parts are mutually turned at prescribed moments. The article shows the algorithm for calculation of spine stress state, and spine curve correction for given brace with adjusted telescope forces. The second algorithm calculates the telescope forces for demanded spine curve correction. The computer program can be used for computer aid design of brace forces. The force effect of the new type of brace is demonstrated on a 14 months old boy with congenital scoliosis of lumbar spine (hemivertebra L1 and L3 on the right side). Curvature measured according to Coob was changed after application of this brace from 47.5° to 32.0°.

Keywords: Scoliosis of Spine, Congenital Spine Defects, Corrective Brace, Computer Aid

Introduction

The children's scoliosis is conservatively treated by the using of corrective braces. The corrective brace is in the Czech rep. individual made according to child's trunk. The negative is made according to the positive plaster form. The Cheneau and/or Cerny brace types the most applies in the Czech Republic. These braces correct spine curve deformities at frontal and sagital planes but the correction cannot be regulated. The corrective brace which is used in the day time cannot be effective used at night too because the child's body has different parameters at horizontal position. The ideal night brace is several centimeters longer and more slanted then the brace for using in the day time.

The newly developed brace with regulated force effect is more effective mainly for night use.

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.

Patients and methods

The newly developed brace with regulated force effect (Figure 1) consists of 3 parts stiff plastic shells which are mutually connected by a pair of ball joints and by telescopes at opposite

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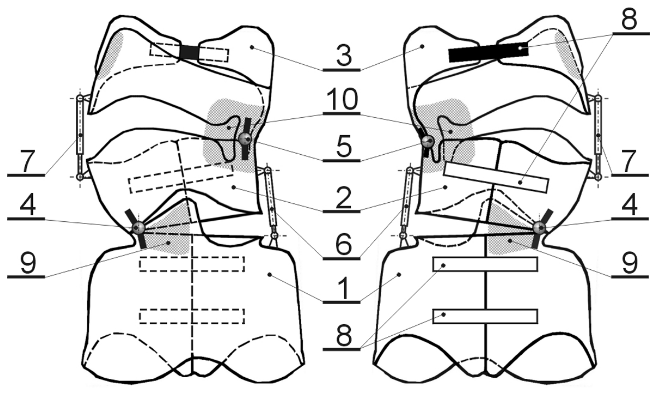

Figure 1. Brace with regulated force effect. (**1**) lumbar part, (**2**) central part, (**3**) thoracic part, (**4**) pair of ball joints connecting lumbar and central parts, (**5**) pair of ball joints connecting central and thoracic parts, (**6, 7**) telescopes with adjustable forces connecting lumbar with central parts and/or central with thoracic parts, (**8**) fasten belts, dry zippers, (**9, 10**) soft lining under ball joints.

sides. The special telescopes were developed to adjust prescribed force values (Figure 2). The telescope forces have moment effects to joints and the same moments turn the child's trunk. The moments operate at frontal place and corrected spine defect at this plane and the brace is appropriated for defect at frontal plane only.

The calculation of stress state at spine and spine deformation correction for given telescope forces and computer aid design of telescope forces are the first and the second tops of the article.

Results

Let F_1, F_2 are telescope forces. The distance of telescopes from joints are r_1, r_2 (Figure 3). Bending moments of telescope forces to joints at frontal plane are calculated from

$$M_i = F_i\, r_i$$

The force effect from brace to a patient trunk was measured with the help of sensors. The brace loads a patient's trunk at places near joints, at lumbar and thoracic ends. The loading has partly parabolic course according to Figure 3. If the distance l from the first loaded lumbar vertebra to last thoracic one is considered 100% then the supported lengths of brace parts are 22.5%, 28.5% and 49%. The lengths of parabolic load was measured with help of sensors and they are a=9, b=19, c=22, d=7 percents of length l (Figure 3).

Telescope forces effect

Let us calculate maximum values of parabolic loadings f_1, f_2, f_3, f_4 (Figure 3) as a force effect of brace to patient's trunk. The parabola f_1 is not symmetric and the other parabolas are symmetric. The moments of telescope forces to joints are equal to moments of parabolic trunk loadings (Figure 3). Let us write the moment conditions of equivalence for the lumbar part of brace to the joint j_1, the lumbar and the central parts of brace to the joint j_2, the thoracic part to the joint j_2 and the thoracic and central parts of brace to the joint j_1 (the parabola area is 2/3 of its bright time height and the gravidity center is at 3/8 and/or 5/8 of its bright).

$$M_1 = f_1\left[\frac{2}{3}a_1\left(\frac{3}{8}a_1 + l_1\right) + \frac{2}{3}a_2\left(l_1 - \frac{3}{8}a_2\right)\right] - f_2\frac{1}{3}b^2\frac{3}{16}\,, \quad (1)$$

$$M_2 = f_1\left[\frac{2}{3}a_1\left(\frac{3}{8}a_1 + l_1 + l_2\right) + \frac{2}{3}a_2\left(l_1 + l_2 - \frac{3}{8}a_2\right)\right] - f_2\frac{2}{3}bl_2 + f_3\frac{1}{3}\frac{3}{16}c^2\,, \quad (2)$$

$$M_2 = \frac{2}{3}dl_3 f_4 - \frac{1}{3}\frac{3}{16}c^2 f_3\,, \quad (3)$$

$$M_1 = -f_2\frac{1}{3}\frac{3}{16}b^2 + f_3\frac{2}{3}cl_2 - f_4\frac{2}{3}d(l_2 + l_3)\,, \quad (4)$$

The measured values a_1=0.03l, a_2=0.06l, b=0.19l, c= 0.22l, d=0.07l, l_1=0.195l, l_2=0.285l, l_3=0.295l are set to the equations and the maximum values of parabolic loads are determined from the formulas

$$f_1 = 91.41106123\frac{M_1}{l^2} + 29.39400808\frac{M_2}{l^2}\,, \quad (5)$$

$$f_2 = 87.38238832\frac{M_1}{l^2} + 38.66340096\frac{M_2}{l^2}\,, \quad (6)$$

$$f_3 = 33.234222\frac{M_1}{l^2} + 57.26026474\frac{M_2}{l^2}\,, \quad (7)$$

$$f_4 = 7.302677104\frac{M_1}{l^2} + 85.22123231\frac{M_2}{l^2}\,. \quad (8)$$

The calculation concurrency can be checked by the vertical force condition of equivalence

$$\frac{2}{3}f_1(a_1 + a_2) - \frac{2}{3}f_2 b + \frac{2}{3}f_3 c - \frac{2}{3}f_4 d = 0\,.$$

The spine will be solved as beam loaded partly by parabolic loads.

The differential equations for the spinal bend curve is

$$EIw'''' = f\,. \quad (9)$$

The spine consists of vertebrae and soft inter-vertebrae tissues – inter-vertebrae discs and ligaments. The vertebrae deformation will be neglected ($El \to \infty$). 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

$$A = 17.9a^2/25,\ I = 26.0044a^4/625. \quad (10)$$

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

$$Q' = -f, \quad M' = Q.$$

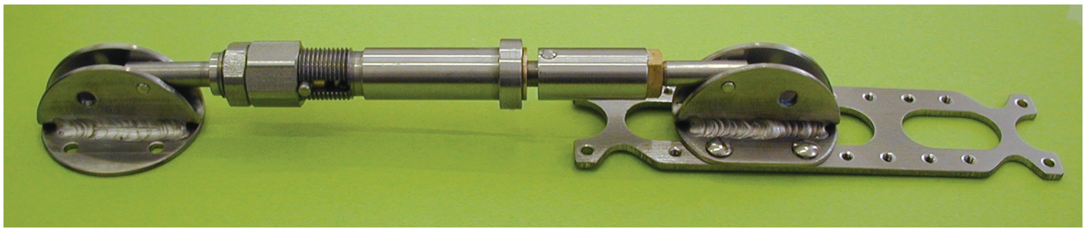

Figure 2. Telescope with regulated forces.

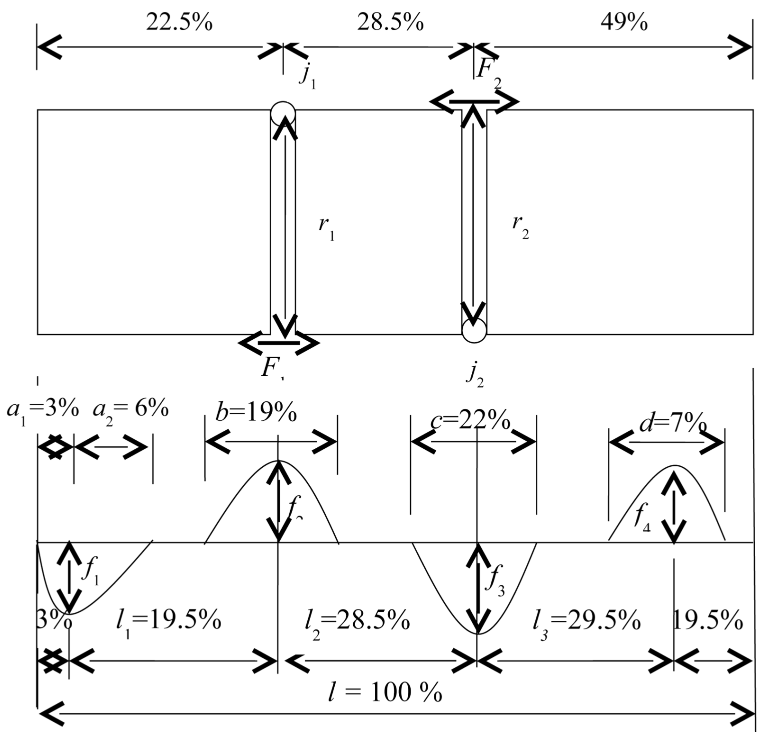

Figure 3. Mechanic brace model and schema of patient trunk loading.

The differential equation (9) 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

$$Q = Q_0,\ M = M_0 + Q_0\xi\ , \quad (11)$$

where Q_0, M_0 are values at interval origin.

Now the loaded spine parts will be solved. The parabolic load (Figure 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

$$Q = Q_1 + \frac{p\eta^3}{3l} - \frac{p\eta^2}{2}\ , \quad (12)$$

$$M = M_1 + Q_1\eta + \frac{p\eta^4}{12l} - \frac{p\eta^3}{6}\ . \quad (13)$$

The movement w and turning φ are given more precisely by differential equations

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

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

$$\varphi = \varphi_0,\ w = w_0 + \varphi_0 \xi \ (14)$$

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

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

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 follow formulas are for differential equation (9)

$$\varphi = \varphi_0 - \frac{1}{EI}\left(M_0 \xi + Q_0 \frac{\xi^2}{2}\right),\ (15)$$

$$w = w_0 + \varphi_0 \xi - \frac{1}{EI}\left(M_0 \frac{\xi^2}{2} + Q_0 \frac{\xi^3}{6}\right).\ (16)$$

The positive direction of used values (sign rule) is follow (directions according to Figure 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.

The displacement w and turning φ at vertebra parts is calculated according to (12) and at parts of inter-vertebrae discs can be calculated according to formulas

$$\varphi = \varphi_0 - \frac{1}{EI}\left[M_1(\eta - \eta_1) + Q_1 \frac{\eta^2 - \eta_0^2}{2} + \frac{p(\eta^5 - \eta_0^5)}{60l} - \frac{p(\eta^4 - \eta_0^4)}{24}\right],\ (17)$$

$$w = w_0 + \varphi_0 \xi - \frac{1}{EI}\left[M_1 \frac{(\eta^2 - \eta_0^2)}{2} + Q_1 \frac{(\eta^3 - \eta_0^3)}{6} + \frac{p(\eta^6 - \eta_0^6)}{360l} - \frac{p(\eta^5 - \eta_0^5)}{120}\right],\ (18)$$

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)

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

The vertebra number has to be set as a real number.

The calculation starts with initial conditions $w_0=0$, $\varphi_0=0$, $M_0=0$, $Q_0=0$ and it is repeated at all vertebrae and inter-vertebrae intervals. The results w_i, φ_i, M_i, Q_i at the ends of intervals are calculated according to formulas (11) to (18) 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 $w_f=0$.

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

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

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

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

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

$$y = \frac{y_i}{l}\xi\left(2 - \frac{\xi}{l}\right)\ (19)$$

for middle segment

$$y = y_{i-1} + \frac{(y_i - y_{i-1})\xi^2}{l^2}\left(3 - 2\frac{\xi}{l}\right)\ (20)$$

and for last segment

$$y = y_{i-1}\left(1 - \frac{\xi^2}{l^2}\right),\ (21)$$

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

$$\varepsilon = \sum_{i\%1}^{n}(w_i - w_{i,ideal})^2.\ (22)$$

The values F_1, F_2 will be searched by method of maximum slope of error ε with numerical calculation of partial derivations. If the error ε is not less then previous error then the step of numerical calculation is halved. Every value with lesser errors is stored. The calculation is finished if the steps $step_1$, $step_2$ of forces F_1, F_2 (occurrence of telescope forces) are less than the given value. Because the calculated spinal curve has not the same form as ideal correction curve, the final error ε will not be zero.

Let's show the calculation algorithm for determination of optimal value of telescope forces. The calculation of maximum values of parabolic loads f_1, f_2, f_3, f_4 for given forces F_1, F_2 and their moment effects to joints (formulas (1) to (4)), solving of differential equation (9) using beam theory and calculation of error ε from (22) is designated "spine solving and its error ε".

1. Choice of initial values according to previous experiences: F_1, F_2, $step_1$, $step_2$
2. "spine solving and its error ε_{old}"
3. Cycles: **for** i=1 **to** 50; **for** j=1,2
4. $F_{old,j}=F_j$; $F_j=F_j+step_j$
5. "spine solving and its error ε"
6. $S_j=\varepsilon-\varepsilon_{old}$; **if** $S_j>0$ **then** ($S_j=-S_j$; $step_j=-step_j$, $F_j=F_{old,j}$) **else** ($\varepsilon_{old,j}=\varepsilon$, $F_{old}=F_j$)
7. Repetition of cycle j
8. $S_{total} = \sqrt{(S_1^2 + S_2^2)}$; $F_1 = F_1 - step_1 * S_1/S_{total}$;

   $F_2 = F_2 - step_2 * S_2/S_{total}$
9. "spine solving and its error ε"
10. **If** $\varepsilon>\varepsilon_{old}$ **then** ($F_{1,old}=F_1$; $F_{2,old}=F_2$; $step_1=step_1/2$, $step2=step_2/2$) **else** $\varepsilon_{old}=\varepsilon$
11. If $\sqrt{step_1^2 + step_2^2}$ < given occuracy the output of F_1, F_2 and stop
12. Repetition of cycle i
13. Output message "Given accuracy was not reached" and stop

Discussion

Ribs and pelvis enable only a few deformations of trunk soft tissues. The soft tissues can be noticeably compressed under central part of brace only and the deformation is relatively small. 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 article volume doesn't permit both methods to be published.

The algorithm has as input values measured values of the brace: l – length of brace and r_1, r_2 – distances between brace telescopes and joint; measured values on X-ray: extremes of pathologic spinal curve and brightness of lumbar vertebra a. The first algorithm has the telescope forces as an input and spine deformation as the result. The second algorithm (computer aid design) has the ideal spine form as input and the telescope forces as the result. It needs the telescope forces estimate only. The algorithm using FEM method uses besides previous values as input a thickness and brightness of compressed soft tissue.

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

Conclusion

The presented type of brace is appropriate for type of defect according to King 1, 2, 3 ('S' defect type) and isn't suitable for defect type King 4. The brace consists from two stiff parts only and one pair telescopes and joints is better for this case. The calculation algorithm is similar and isn't published at this paper.

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