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Original Article

Biomechanics of leg deformity treatment

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Abstract

At pre-school age, there is a possibility to treat severe varosity and/or valgosity of legs by orthoses. The three points force effect of the orthosis partially corrects the pathologic defect of the leg. If the orthosis is intermittently used for a long time the correction is permanent. Step by step correction of bone deformities are based on remodelling of growth epiphyses and bones that are caused by orthotic bending pre-stressing. According to Hüter-Volkmann's law, the oblique loading regulates the growth of epiphyseal plates of long bone into the direction of the pressure result and the bone remodelling process is started: it means that the bone grows at the tensile part of growth epiphyses more quickly than at pressure one and gradually eliminates the varosity and/or valgosity defect. The knowledge of stress values for starting of the bone remodelling process is principal for clinical praxis. The values of pre-stressing cannot be increased by starting the remodelling process from the ethical point of view but it can be judged on its starting according to the success of the treatment. The aim of this article is to study the bone, ligament stress state and deformations of successful treatment. Method and calculation algorithm of stress state and deformation that are necessary for the starting of the remodelling process at the knee region were verified on a group of eight patients that were fitted by orthoses with bending pre-stressing. The space models of the knee, femur and tibia were composed with the help of X-ray, CT and MRI scan. The calculation algorithm was implemented on a PC and the program can be easily applied at clinical praxis.

Keywords: Varosity, Valgosity, Stress State, Ligament Forces, Biomechanics of Leg Deformities

Introduction

Idiopathic varosity and valgosity are the most common deformities leg of the child (Figures 1a, 1b, 3). These leg deformities often attend the growth in children suffering from bone dysplasias. There is normal development of tibiofemoral angle in children of a pre-school age[1] (Figure 3). Deformities are usually measured on X-ray pictures of legs carried out in a standing position. The *tibiofemoral (T-F) angle* describes the axial relationship of the femur and tibia in the frontal plane. This angle is formed by the lines drawn along the femur and tibia and it is called *anatomic axis*. The normal T-F angle is 5° to 7° (3° to 8°) valgus[1-3]. The valgosity (*genu valgum, knock knee*) is a part of the physiological development of many normal children. Children aged between 3 and 3.5 years old had a knock knee. Over 95% of the knock knee corrects spontaneously by the age of 6 to 7 years to about 6°. The varosity (*genu varum, bow leg*) may result from lateral curvature involving either the tibia or the tibia and the femur. A minor degree of this deformity is very common in children during the first or second year of life. The spontaneous correction is likely to occur by the time the child is 4 or 5 years old[3]. Presently, the varosity and valgosity leg of the child are assessed as intercondylar or intermalleolar distance, respectively. In our clinical praxis we introduced a measurement of tibiofemoral angle from photos of children in standing and lying position. Children with severe remaining valgosity (after the age of 6 years) and/or varosity (after the age of 4 years) can be successfully conservatively treated by orthoses with bending pre-stressing. In the Czech Republic new corrective orthoses with bending pre-stressing were developed and introduced for the treatment of leg deformities and joint contractures in children with idiopathic deformities of the legs, congenital and acquired disorders of the skeleton in 1997. The orthoses consist of two parts that are jointed by a hinge (on the lateral or medial side) and the telescope on the opposite side. The application of orthoses is demonstrated at Figure 3. The

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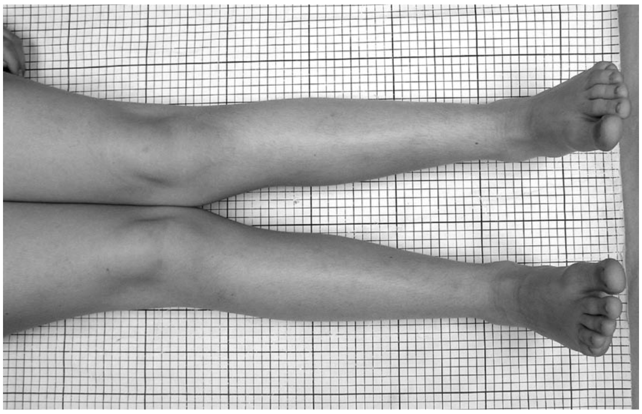

Figure 1a. Valgosity of legs of a boy with epihyseal dysplasia at the age of 12 years. Height 152 cm, weight 52 kg, intermalleolar distance 11.5 cm, tibiofemoral angle 21° on the right leg and 16° on the left one.

special screws with spring telescope were developed with the possibility to measure and keep steady pre-stressing (Figure 2).

The orthosis with bending pre-stressing has a three-point force (bending) effect on the leg[2,9]. It therefore returns to its previous shape if the orthosis is taken off. But intermittent (around 10 hours through the night) and long time (approximately months-years) application of the orthosis causes remodelling of growth epiphyses and therefore the deformity is gradually eliminated[9]. It can be explained according to the Hüter-Volkmann law (the growth is restricted at the overloaded part of the epiphyseal plate and at the unloaded part the growth is accelerated) when bending loading induced by the orthosis regulates the growth of epiphyseal plates of long bone into the direction of the pressure resultant[5-8]. The bone remodelling process is started. It means that the bones grow at the tensile part of the growth epiphyses more quickly than at the pressure one and varosity and/or valgosity defect is gradually corrected. The knowledge of stress values for the beginning of bone remodelling process is principal for clinical praxis. The values of pre-stressing cannot be increased step by step (without any treatment effect) to begin the remodelling process from an ethical point of view.

The aim of the article is to study the bone and ligament stress state and deformations. Initiation of bone remodelling can be judged according to the successful treatment and their stress and deformation values.

From a biomechanical point of view, the efficacy of orthosis continues for some time even when the orthosis is taken off. It can be explained by *deformational-rheological theory* of remodelling[11]. According to this theory the existence of remodelling effects even during a rest can be explained.

The femur and tibia stress stay, ligament forces and deformations are observed as an orthosis force effect for patients with successful treatment. The calculation algorithm for computer is presented. The results show support values for clinical praxis.

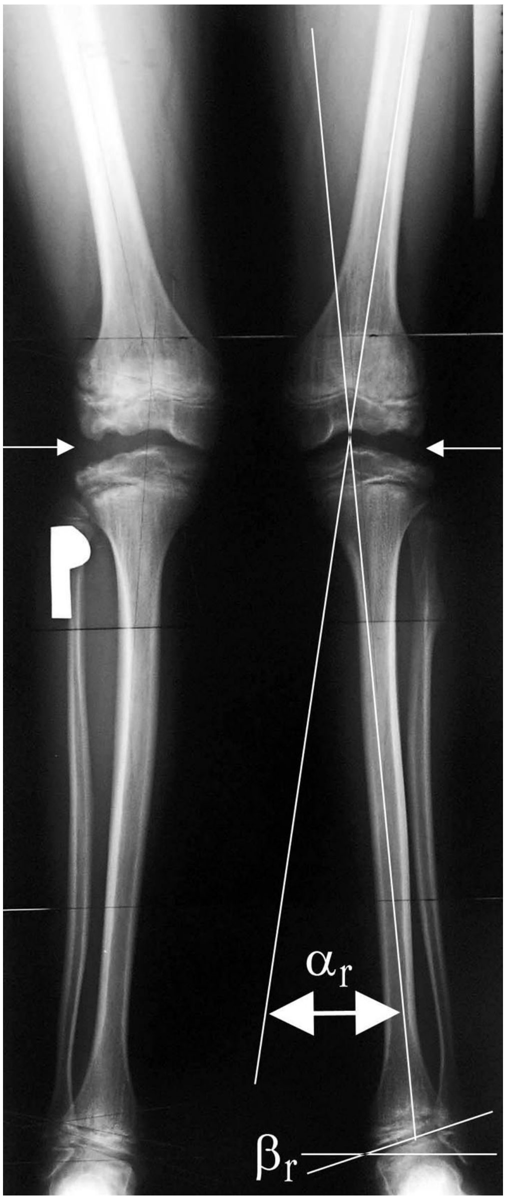

Figure 1b. X-ray of legs in standing of the same boy at the age of 12.5 years. Tibiofemoral angle $\alpha_r = 16°$.

Patients and methods

Bone deformities treatment are studied and the calculation algorithm of bone and ligament stresses and deformation are shown in a group of eight children who were treated due to severe valgosity or varosity of knees at the Ambulant Centre for Defects of Locomotor Apparatus in Prague (Czech Republic). The orthoses were individually made at the Czech firm "Ortotika" according to plastic forms of patients legs[9]. The input data are: the dimension of a patient's knee, the dimensions of femur and tibia at the level of growth plates, the orthosis position, the force of telescope and the distance between the telescope and hinge of

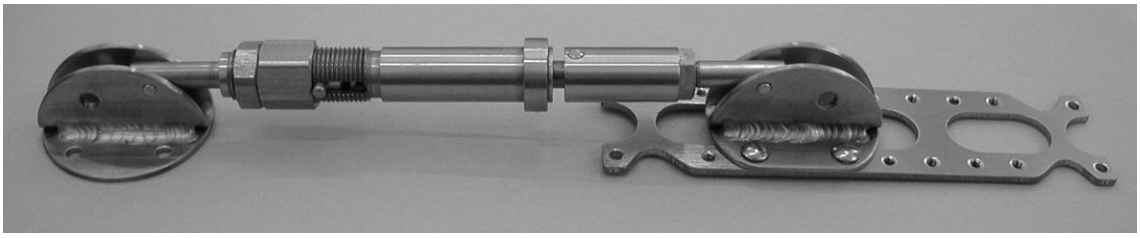

Figure 2. Telescope with adjustable pre-stressing force.

orthosis (Figure 2). The cross-section form at the growth plate and the knee shape was obtained by CT and MRI scans for one of the cured patients only. The cross-section forms were divided into triangles and their characteristics were calculated[4]. The cross-section characteristics need not be obtained for each patient but the moment of inertia of growth plate, the cross-section areas of ligaments and meniscus were calculated for one patient and transformed by scale factors to the other patients.

The orthoses consist of femoral and tibia parts. Both parts are connected with a hinge and telescope on the opposite side (Figure 2). The orthosis bending moment effect on the patient's knee is equal to the screw force time of the distance between the telescope and hinge. The telescope forces, its distances from hinge and bending moments of a group of patients are presented at Table 1. The mutual turning of the two parts of orthosis consists of these influences: knee deformations (ligament stretch and compression of joint cartilage and growth plate deformation), orthosis deformation, motion of the leg at orthosis (deformation of soft pads of orthosis) and a compression of leg soft tissues. The bone deformations are neglected.

The leg loading is derived from the equilibrium condition of the orthosis telescope and hinge forces (external forces) and leg reaction forces (internal forces). The bone stress state is calculated according to the prismatic beam theory using Navier/ Bernoulli's hypothesis (the cross-section carries planning after a deformation, too). The bone stress state is calculated at the growth epiphysis. The calculation needs knowledge of the cross-section moment of inertia at the growth plate. The side ligament stress, its deformation and femur and tibia mutual rotation are solved as the second problem.

The numerical calculation was applied for a group of eight patients. The critical bone and ligament stress state and strength state was searched for starting of the bone remodelling process. From the observed successful treatment it can be judged according to the initial remodelling values.

Results

Leg deformation as the orthosis force effect

The following calculation uses these values: elasticity modulus of ligaments 303 MPa and of cartilage 10.5 MPa (at the linear part of stress/strain dependence), the strength of ligament 29.5 MPa[10].

The calculation algorithm for bone stress state and knee deformation for patients with successful leg deformity treatment will now be presented. The algorithm was used for a group of eight patients. The input values and results are introduced at Table 1, 2. The numerical interpretation will be presented as an example for one concrete patient with valgosity (patient 1 at Table 1, 2). The measured values which are used as input values in the algorithm are presented at Table 1. The follow values were measured: *F* - screw force, *a* - perpendicular distance between telescope and hinge of orthosis, c_1 - perpendicular distance from ligamentum collaterale laterale and the centre of meniscus medialis, c_2 - perpendicular distance from ligamentum collaterale mediale and the centre of meniscus lateralis, A_{m1}, A_{m2} - transversal areas of meniscus medialis and lateralis, A_{v1}, l_1 - cross-section area and length of ligament collaterale fibulare, A_{v2}, l_2 - cross-section area and length of ligament collaterale tibiae, b_1, b_2 - frontal diameter of femur and/or tibia growth plates. All values of the patient's knee were measured by X-ray, CT and MRI scanning.

The orthosis bends the knee with moment M (telescope force F times measured distance between the telescope and hinge of orthosis):

$$M = F.a = 32{,}5\text{x}0.16 = 5.2 \text{ Nm}$$

The same moment has to be as reaction at the knee, because the ligament tensile and cartilage compress forces R are (the distance c_1 between lateral ligament and the center of joint cartilage at the opposite side of the knee is 5.6 cm):

$$R = M/c_1 = 5.2/0.056 = 92.857 \text{ N}$$

The stress at meniscus medialis is:

$$\sigma_{m1} = \frac{R}{A_{m1}} = \frac{92.87}{8.88.10^{-4}} = 104568.85Pa = 104.568kPa$$

The compression of meniscus medialis with thickness t=6.15 mm is:

$$\Delta_1 = \frac{\sigma_{m1}}{E_m} t = \frac{104.568}{10500} 6.15 = 0.06126mm$$

The side ligament stress state is:

$$\sigma_v = \frac{R}{A_v} = \frac{92{,}857}{28{,}29.10^{-6}} = 3.2823.10^6 Pa = 3.2823MPa$$

The dependence between stress σ_v and strain ε_v at ligaments is shown at Figure 4. The ligament fiber tensile has the follow-

Patient	F – [N]	a – [cm]	M – [Nm]	c_1 – [cm]	A_m – [cm^2]	l_1 – [cm]	l_2 – [cm]	A_{v1} – [cm^2]	A_{v2} – [cm^2]	d_f – [cm]	d_t – [cm]
1	33	16	5.2	8.88	6.3	6.3	9.6	28.29	65.78	8.2	6.3
2	70	14	9.8	6.1	9.91	5.1	11.2	32.17	64.42	8.0	6.9
3	87	17	14.8	6.8	11.17	5.5	9.9	41.22	81.53	8.5	7.9
4	87	19	16.6	9.0	20.87	7.3	13.3	73.28	144.94	11.0	9.7
5	70	12	8.4	6.3	10.44	4.6	9.2	35.34	69.9	7.4	6.6
6	53	12	6.4	4.5	5.09	4.3	7.2	16.34	32.32	6.2	4.9
7	70	13	9.1	6.0	9.26	4.5	8.7	22.62	44.74	7.7	6.4
8	53	9.5	5.0	3.5	3.28	3.9	6.15	7.69	15.22	4.9	3.5

Table 1. Measured values (F - screw force, a - perpendicular distance between telescope and hinge of orthosis, c_1 - perpendicular distance from ligamentum collaterale laterale and the centre of meniscus medialis, c_2 - perpendicular distance from ligamentum collaterale mediale and the centre of meniscus lateralis, A_{m1}, A_{m2} - transversal areas of meniscus medialis and lateralis, A_{v1}, l_1 - cross-section area and length of ligament collaterale fibulare, A_{v2}, l_2 - cross-section area and length of ligament collaterale tibiae, b_1, b_2 - frontal diameter of femur and/or tibia growth plates).

Patient (results for valgosity/ varosity)	R – ligament force [N]	σ_v – ligament stress [MPa]	Δ_2 – ligament elongation [mm]	α – T-F angle effect [grad]	σ_{femur} – max. stress at femur [MPa]	σ_{tibia} / – max. stress at tibia [MPa]
1	93/84	3.28/1.28	1.98/2.39	2.10/2.30	1.41	3.12
2	52/47	1.83/0.71	1.58/2.26	1.59/2.07	0.88	1.64
3	161/146	5.00/2.68	1.90/3.16	1.87/3.80	2.87	4.47
4	113/103	3.52/1.60	1.94/2.93	1.88/2.58	2.10	3.15
5	218/198	5.28/2.43	2.10/2.84	1.86/2.29	3.61	4.50
6	228/207	5.52/5.54	2.02/2.82	1.89/2.38	3.88	6.20
7	184/168	2.52/1.16	2.12/3.26	1.38/1.93	1.87	2.72
8	187/170	2.55/1.17	2.10/3.27	1.38/1.95	1.77	2.64
Average	154/140	3.69/1.64	1.97/2.87	1.74/2.29	2.30	3.56

Table 2. Results of calculation (R - ligament force, σ_v - ligaments stress, Δ_2 - ligament elongation, α - T-F angle as knee deformation effect, σ_{femur}, σ_{tibia} - maximal stress values at femur and/or tibia growth plates).

ing stages: a - fibers are straightened, b - fibers are protracted, c - any fibers are destroyed and d - ligament is destroyed. The partly linear dependence will be used according to stage A - the fibers protract with zero stress till $\varepsilon=\varepsilon_R/4.5$ and B-the dependence is lineal to strength of ligament equal 29.5 MPa. The corresponding limit strain is:

$$\varepsilon_R=\sigma_R/E=27.5/303=0.09076 \text{ and } \varepsilon_R/4.5=0.02017$$

The protract of ligament is:

$$\Delta_2=\left(0.0207+\frac{\sigma_v}{E_v}\right)l_1=\left(0.0207+\frac{3.2823.10^6}{303.10^6}\right)0.063=$$
$$=0.001987m=1.987mm$$

The change of T-F angle under orthosis force effect is:

$$\Delta_\alpha=\frac{\Delta_1+\Delta_2}{c_1}\frac{180}{\pi}=\frac{0.06126+1.987}{56}\frac{180}{\pi}=2.906\_grad$$

The results for the group of patients from Table 1 are presented at Table 2. The output stress values are the maximum of stress at the femoral and/or tibia growth plate, the lateral ligamentum stress and stretch and the tibia-femoral angle correction when the orthosis is applied. The correction has these causes: side ligament stretch, meniscus compression, compression of leg soft tissues and orthosis deformation.

The remodelling useful stress and stretch values for a group of patients are introduced at Table 2.

The calculation accuracy of bone stress state and knee deformation depends on correctly measured input values. The measured values for eight patients are presented at Table 1 (F - telescope force, a - distance between the telescope and hinge, M - orthosis moment, A_m - meniscus area, l_1, l_2 - lengths of lateral and medial ligaments, A_{v1}, A_{v2} - lateral and medial ligament areas, d_f,

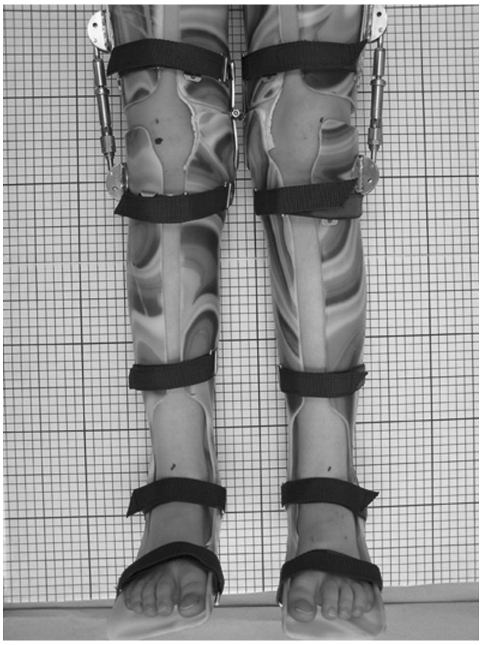

Figure 3. The same boy as in Figure 1a. at the age of 12 years with two orthoses. There is evident correction of intermalleolar distance, tibiofemoral angles of both leg knees are 8°.

d_t - width of femur and/or tibia at the level of growth plate in the frontal plane). The results according to previous algorithms are in Table 2 (R - ligament force, σ_v - ligament stress, Δ_2 - ligament elongation, α - T-F angle as knee deformation effect, σ_{femur}, σ_{tibia} - maximal stress values at the femur and/or tibia growth plates). The results for valgosity are situated in the first row for each patient and results for varosity in the second one. The average values are shown in the last two rows.

Bone stress state

The bone stress state can be calculated by the finite element method or the femur and/or tibia can be solved as a prismatic beam according to the Navier/Bernoulli hypothesis.

If the finite element method is used the bone has to be divided into different elements. A more convenient variant of stress state calculation at the growth plate is the linear beam theory. The growth epiphysis is supposed as a plane cross-section perpendicular to the bone axis. The linear beam theory according to the Navier/Bernoulli supposes the hypothesis that the plane bone cross-section is plane after deformation, too. The maximal stress at the growth plate is:

$$\sigma_{\max}=\frac{\mathrm{M}}{W},\ W=\frac{J}{y_{\max}} \tag{1}$$

where M is the beam moment at the place of growth epiphysis, W is cross-section modulus, J is the moment of inertia for bone cross-section at the transversal plane to z - axis parallel with medial plane and y_{max} - distance the farthest cross-section point from the z axis. The values J and y_{max} were measured by CT. If the orthosis hinge has its position at the level of theepiphyseal plate then the bending moment has maximal value for the whole femur (tibia) and it is equal to the moment of telescope force to hinge.

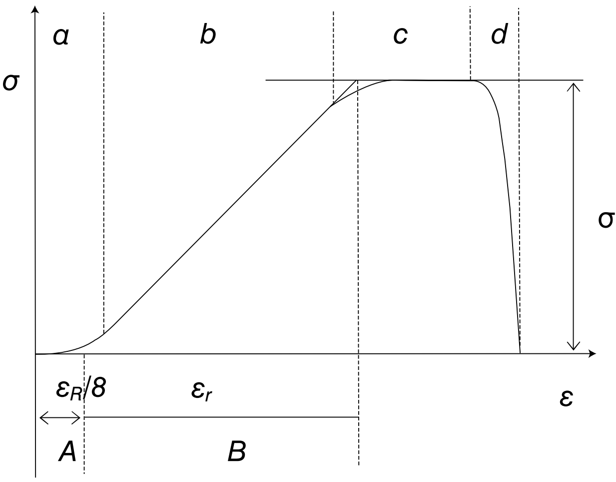

Figure 4. Graph of depending ligament stress and strain.

The cross-section characteristics W, resp. J, y_{max} is not necessary to determine for each patient but anatomic similarity may be used. The value W was determined for the patient having bone width at the level of the growth plate at frontal projection 5 cm. The value was determined with the help of CT projection and it was calculated by computer program MOMSET_[4].

$$W_{5cm}=8{,}3383\ \mathrm{cm}^3=0{,}83383.10^{-5}\ \mathrm{m}^3$$

The cross-section modulus for an observed patient is:

$$W=W_{5cm}\left(\frac{b}{5}\right)^3 \tag{2}$$

where b [cm] is the femur width at the level of growth epiphysis at the frontal plane.

The investigated patient has b_1=8.2 cm at the femur growth plate and b_2=6.3 cm at the tibia growth epiphysis. The cross-sectional modules are (see (2)):

$$W_1=W_{5cm}\left(\frac{d_1}{5}\right)^3=0{,}83383.10^{-5}\left(\frac{8.2}{5}\right)^3=3{,}678.10^{-5}m^3$$

$$W_2=W_{5cm}\left(\frac{d_2}{5}\right)^3=0{,}83383.10^{-5}\left(\frac{6.3}{5}\right)^3=1{,}668.10^{-5}m^3$$

The maximal stress at the femur growth plate is (see (1)):

$$\sigma_{\max}=\frac{\mathrm{M}}{W_1}=\frac{5{,}2}{3{,}678.10^{-5}}=1{,}4138.10^6Pa=1{,}4138MPa$$

and at tibia growth epiphysis:

$$\sigma_{\max}=\frac{\mathrm{M}}{W_2}=\frac{5{,}2}{3{,}668.10^{-5}}=3{,}1175.10^6Pa=3{,}1175MPa$$

The tensile stress is on the hinge and pressure stress on the opposite side.

Discussion

The maximal values of stress for presented patients are according to tab. 2 at bones 6.2 MPa and 5.52 at ligaments. The calculated values are less than the ultimate stress values 133 MPa for bones and 10.4 MPa for ligaments[10]. That is why treatment with orthoses is not dangerous.

The stress state algorithm at the level of the growth plate has very good accuracy because the bending moment can be determined with very good accuracy and the prismatic beam theory gives good results, too.

Bending pre-stressing at the knee joints caused by orthoses is sufficient for starting bone remodelling. The epiphysis plate has grown at the tensile side more quickly than at the pressure one. The calculation of stress state for eight patients was introduced as an example. This paper is focused on the study of the bone and ligament stress state and deformations of successful treatment when the remodelling process is started.

Long-term clinical and anthropological assessment of a cohort of Czech children with so-called idiopathic deformities of legs fitted with orthoses with bending pre-stressing is prepared for publication.

Conclusion

The shown method and calculation algorithm of stress state and deformation that are necessary for starting the remodeling process at the knee region were verified on a group of eight patients who were fitted with bending pre-stressing orthoses made at the Czech firm Ortotika and followed at the Ambulant Centre for Locomotor Defects in Prague, Czech Republic.

The stress state for starting remodelling is not the same for each patient due to age, sex, constitution, physical properties of bone, cartilage and fibrous tissue, etc. Successful orthotic treatment can be presumed if an orthopaedist uses the same parameters of orthosis (the same bending pre-stressing) and the same treatment regime. The calculation algorithm was implemented on PC and the program can be easily applied at clinical praxis.

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