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A Biomechanical Analysis of the Etiology of Tibia Vara

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Summary: To elucidate the cause of tibia vara, finite element analysis of the proximal tibia was used to investigate the stresses occurring in the physeal plate during one-legged stance in 2- and 5-year-old children. A modification of the method of Kettlekamp and Chao was used to assign forces to the medial and lateral plateaus and lateral ligament. Stresses were calculated in the physeal plate for the two age groups as a function of degree of varus and body weight. Our results show that increasing varus resulted in increasing compressive stress in the medial tibial physis to a level seven times normal at 30° of varus. Further, tensile stresses determined in the lateral tibial physis were increased above normal. Changes were more marked in the obese child and in the 5 year old. Using the data from Strobino et al. it appears that in the 2 year old 20° of varus resulted in forces sufficient to retard growth. In the 5 year old, however, 10° of varus resulted in borderline forces in a child of normal weight, but forces exceeding those necessary to retard physeal growth were calculated in the model of the obese child. Our data are consistent with the hypothesis that Blount's disease is primarily the result of the proximal tibial epiphysis responding to physical phenomena. **Key Words:** Tibia vara—Biomechanics—Stress analysis.

Currently Blount's disease (tibia vara) is thought to be an acquired disease of the proximal tibial metaphysis (16) rather than an epiphyseal dysplasia or avascular necrosis. Several clinical observations contribute to this conclusion. Weight bearing seems to be necessary for the disease to occur, since Blount's disease is virtually never diagnosed before 2 years of age, after at least 1 year of walking. Further, the disease is never seen in nonambulatory patients. The radiographic picture of Blount's disease is a progressive one in which the early X-ray films are deceptively benign. Radiographic measurements by Levine and Drennan (16) have localized the deformity to the physeal-epiphyseal area rather than the tibial or femoral diaphysis, but the changes are subtle especially in the early stages. Early osteotomy, presumably normalizing the stresses on the epiphysis, is almost always curative (16,17).

The exact cause of Blount's disease is a subject of much controversy. The present prevalent concept is that tibia vara is a growth abnormality of the proximal medial physis of the tibia, caused by abnormal stresses on the epiphysis, in response to the Heuter-Volkman law (increased pressure on an epiphysis inhibits growth) (1). Delpech's law extends this concept to stimulation of epiphyseal growth by release of pressure (1). It follows that compressive stress to the medial epiphysis should cause a slowing or cessation of growth with a subsequent varus deformity of the proximal tibia. Similarly, Delpech's law predicts a stimulation of growth of the lateral epiphysis, which would worsen the deformity.

Various investigators have attempted to deduce the cause of tibia vara from clinical data. Blount (5) thought that a congenital factor was operative in the infantile form with trauma more important later. Bateson found that Jamaican children had more severe "physiological" bowing and also walked at an earlier age, presumably predisposing them to de-

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velop tibia vara (2,3). Golding and McNeil-Smith noted similar findings in black African children (11). Bathfield and Beighton, on the other hand, found no relationship of joint laxity, physiological bowing, age of walking, or postural habits that could be predisposing factors (4). Levine and Drennan found that, although the majority of children were in the 90th percentile by weight, the control group of physiological bowlegs was equally overweight (16). Recently, Kling hypothesized that tibia vara is a progression of physiological bowing due to mechanical stress to the proximal medial epiphysis (15). The etiology, however, is still uncertain (22), and there is presently no explanation as to why tibia vara is more prevalent in black children.

The effect of pressure on the growth plate has been studied by a number of investigators. Strobino et al. placed wires across the epiphysis of calves and found that epiphyseal growth could be stopped (23). The magnitude of the force (or stress) that was required is a matter of controversy due to experimental design and interpretation of their results. Strobino et al. have been referenced as stating that values of 645 N (145 lb) (6,11) and greater than 1,780 N (400 lb) (1) are necessary to stop epiphyseal growth. Arkin and Katz maintained that the effect of pressure on epiphyseal growth was not an all-or-none phenomenon and there is no threshold below which pressure is ineffective (1). Porter studied epiphyseal growth under tension and found accentuation of growth (20) in accordance with Delpech's law. This has been noted clinically in bowlegged children by Currarino and Kirks (7). These findings are consistent with Frost's chondral modeling theory, which states that an increase in tension or compression results in a growth rate increase, and pressure above a critical level results in growth inhibition (10).

Despite the fact that this growth disturbance has been attributed to mechanical factors, little information has appeared on the relevant biomechanics. Kettlekamp and Chao (14) have reported an analytical determination of the tibial contact and ligamentous forces in normal and degenerative adult knees, but no study has been directed toward elucidating the mechanical factors in tibia vara. The objective of the present study was to investigate the mechanical factors involved in the pathophysiology of Blount's disease by examining the loading configuration and stress distribution in the proximal tibia of normal children and children with tibia vara.

MATERIALS AND METHODS

The finite element model (FEM) was used to study the stress distribution in the proximal tibia. Finite element analysis is a numerical approximation technique in which a structure is idealized into an assemblage of finite regions (elements). These elements are considered connected at common boundaries (nodes), and a set of governing equations is generated by means of the stiffness of the idealized structure. Assumptions inherent on the formulation of the FEM as well as material, geometric, and loading considerations of the model are critical in determining the accuracy of the finite element results, and thus all results must be considered approximations of the actual behavior. Details of the FEM can be obtained from standard structural engineering texts (9,24).

A two-dimensional plane stress FEM of the proximal two-thirds of the tibia of a child was constructed. The material and the geometric configuration of the elements in the model were determined based on the morphology of radiographs of normal children. The model was constructed to incorporate the geometry and material property distributions of children of both 2 and 5 years of age to study both age groups (Fig. 1). The resulting FEM used approximately 500 constant-strain triangular and rectangular elements and contained approximately 550 node points. Material elastic properties for the model were obtained from the literature and are referenced in Table 1. A series of model simulations were performed as a function of child body weight, degree of varus, and age. Varus was defined as the angle between the tibia and femur with 0° corresponding to alignment of the axes of the bones.

Loading conditions for the FEM were based on the analysis of Kettlekamp and Chao (14) of knee loading and were modified to incorporate the femoral tilt into the calculations to model the actual "bowlegging" more accurately. The modified Kettlekamp model accounted for both the medial and lateral plateau contact forces, as well as the force in the lateral ligament. Figures 2 and 3 represent the data calculated with the modified Kettlekamp model. Figure 2 shows the compressive force on the medial plateau as a function of degree of varus for both 2- and 5-year-old age groups of normal and obese body weight. Figure 3 shows the compressive force in the lateral plateau and tensile force in the lateral ligament. It should be noted that the modified Kettlekamp model predicts a loss of contact in the lateral plateau at 10° of varus. This is clearly appreciated in Fig. 3, in which a sharp increase in the lateral ligament force is observed at approximately 10° of varus, indicating lift-off of the lateral plateau and tensile loading of the lateral ligament. The force in the lateral ligament increases approximately linearly with increasing degrees of varus. The two body weights investigated corresponded (a) to the 50th percentile of the patient's height group, according to the National Center for Health Statistics (19) physical growth tables (normal body weight), and (b) to the 90th percentile to represent an obese child, since Blount's disease has often been linked to overweight children, particularly early walkers (11,16). The weights used for the 2 year old were 26.4 kg (normal) and 31.9 kg (obese) and for

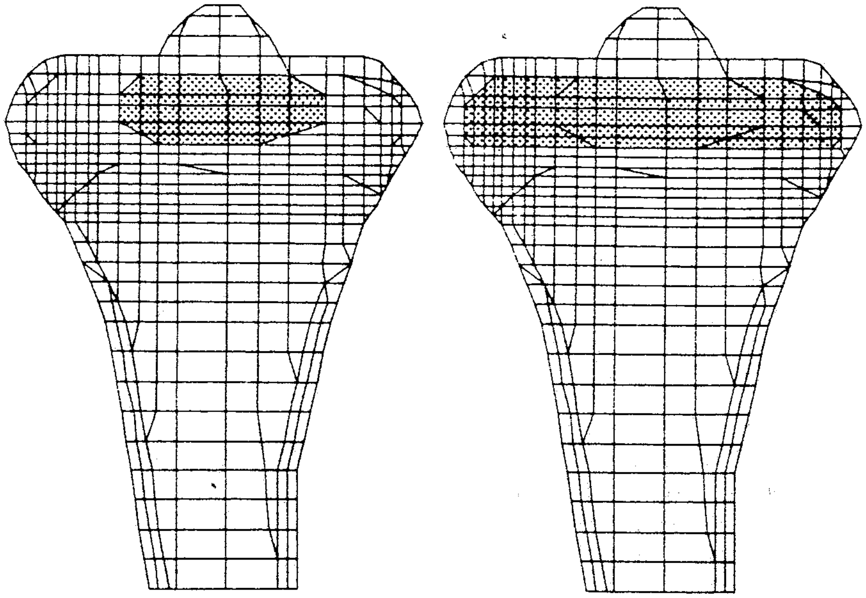

FIG. 1. Finite element models used in the study of 2-year-old (**left**) and 5-year-old (**right**) tibia. Osseous areas in each model are highlighted by shading.

the five year old were 39.6 kg (normal) and 50.6 kg (obese). Appropriate forces on the medial and lateral plateaus and lateral ligament were calculated for both weight classifications and used as input to the FEM.

RESULTS

Plots of the minimum component of the principal stress calculated with the FEM along a medial/lateral line (Fig. 1) in the epiphyseal cartilage are shown in Figs. 4–7 as a function of anatomical location. Figure 4 shows the stresses in the epiphyseal plate for a 5 year old of normal weight as a function of degree of varus. Note that for greater than 10° of varus the minimum stress component in the lateral tibial condyle goes from compression to tension because of the applied bending moment from the lateral ligaments and the lift-off of the femoral condyle from the lateral plateau. The stresses in the tibial epiphyseal cartilage for a 5-year-old child in the 90th percentile for body weight as a function of degree of varus are shown in Fig. 5. It can be seen that there was a generalized increase in stresses both in the medial and lateral plateaus and in the presence of tensile stresses in the lateral plateau consistent with the behavior seen in Fig. 4 for normal body weight. There was nearly a fivefold increase in stress in the medial epiphysis between 0 and 20° varus for both the normal and the obese 5 year old. Varus of 30° increased the medial epiphyseal stress to approximately seven times normal, whereas 10° produced only a twofold increase. It should be noted that in all cases the stresses calculated for the obese child were greater than for the 5 year old of normal body weight.

The stresses calculated by the FEM in the proximal epiphyseal cartilage of the tibia for 2-year-old children of normal or obese body weight as a function of the degree of varus deformity are shown in Figs. 6 and 7. Note again the approximate linear increase of stress with varus deformity and the greater stresses for the obese child. Note also that there was an approximate sevenfold increase in

TABLE 1. *Material properties used in constructing the finite element models*

Material	Modulus (MPa)	Poisson's ratio	References
Articular cartilage	11.6	0.5	12
Trabecular bone			
Intramedullary	350.0	0.2	21
Subchondral	700.0	0.2	8
Compact			
2 year old	8,200.0	0.3	18
5 year old	11,200.0	0.3	18

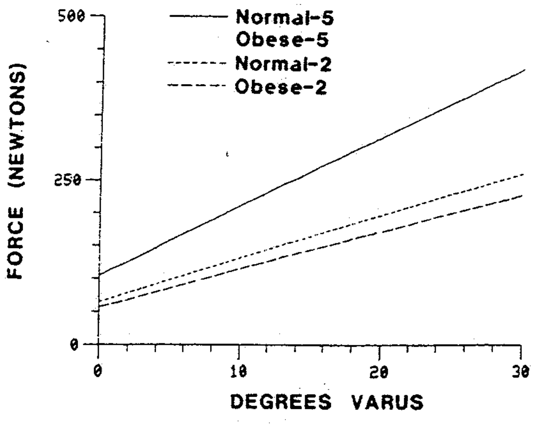

FIG. 2. Force in medial plateau for 2- and 5-year-old children in the 50th and 90th percentiles of weight. Note that the curves for the two weights diverge slightly with increasing degree of varus deformity for both age groups.

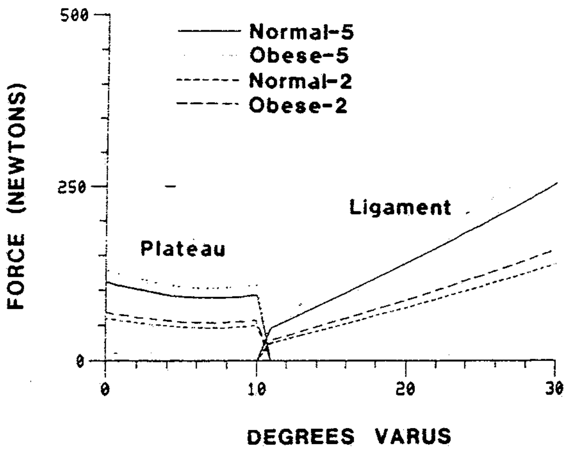

FIG. 3. Force in the lateral plateau and lateral ligament for 2- and 5-year-old children in the 50th and 90th percentiles of weight. Note that tensile stress in the lateral ligament begins at lift-off of the lateral plateau at approximately 10° of varus angulation.

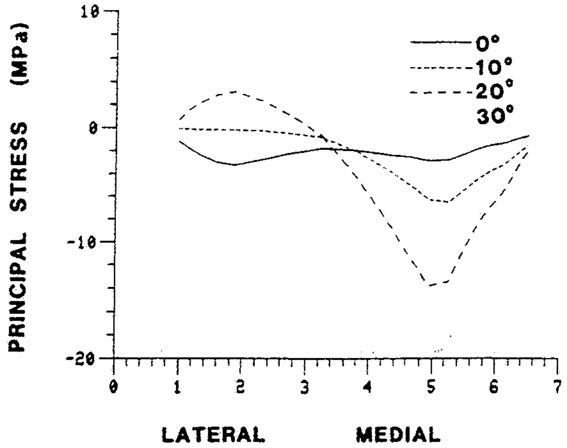

FIG. 5. Minimum component of the principal stresses calculated by the finite element model in the tibia epiphyseal cartilage for a 5-year-old child in the 90th percentile for weight as a function of degree of varus. Note the generalized increased stress both in the medial and lateral plateaus and the lateral tensile stresses consistent with those seen in Fig. 4 for a 5 year old of normal weight.

stress with a varus deformity of 30° for 2-year-old children in the 50th or 90th percentile of weights over that seen in the 5-year-old child.

DISCUSSION

The use of two-dimensional analyses has several obvious limitations. First, there is no way to take into account the presence of internal tibial rotation. Similarly, it is impossible to study localization of loading effects in the sagittal plane, which may be important since the depression in the epiphysis most commonly is found medially and posteriorly. These parameters are currently being studied with the use of a three-dimensional FEM. It should also be noted that the FEM calculates responses to static loading conditions and thus does not reflect load changes and stress changes which occur throughout the gait cycle.

The results of the FEM demonstrate that increased stress is present at the medial epiphyseal plate of the knee under conditions of weight bearing with varus angulation of the knee. The stresses were seen to be increased when the weight of the patient was increased. Increasing varus deformity caused increasingly higher stresses in the medial epiphyseal cartilage. The compressive stresses noted in the varus knee are localized to the area beneath the medial femoral condyle. This accentuation occurs because the lateral condyle at approximately 10° of varus bears no stress at all. Stress values calculated in the medial epiphyseal cartilage of the 5 and the

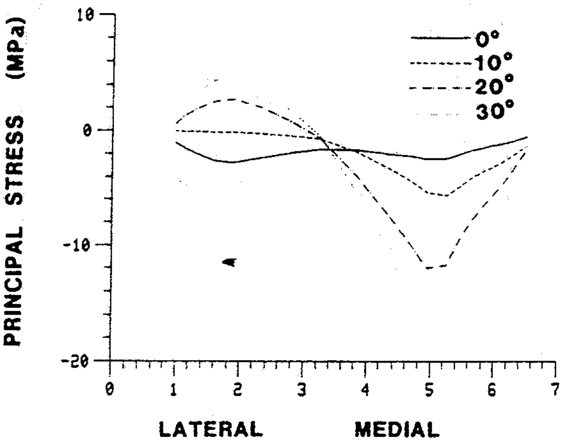

FIG. 4. Minimum component of the principal stresses calculated by the finite element model for the lateral and medial tibia epiphyseal cartilage for a 5 year old of normal weight as a function of degree of varus. Note that for greater than 10° of varus angulation the lateral tibia condyle stress is tensile because of an applied bending moment from the lateral ligaments.

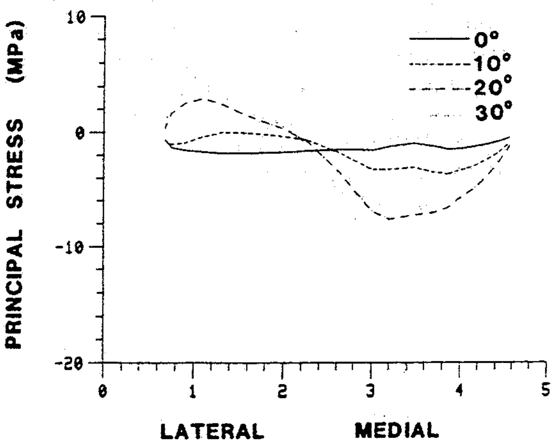

FIG. 6. Minimum component of the principal stresses calculated by the finite element model in the proximal epiphyseal cartilage of the tibia for a 2-year-old child of normal weight as a function of degree of varus. Note the approximately linear increase in stress with varus deformity.

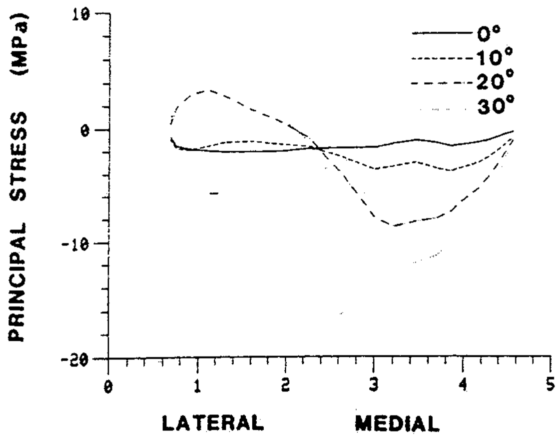

FIG. 7. Minimum component of the principal stresses calculated by the finite element model in the proximal epiphyseal cartilage of the tibia for a 2-year-old child in the 90th percentile of weight as a function of degree of varus. It should be noted that in the 2 year old as in the 5 year old the lateral tibia condyle is subjected to tensile stress from the bending moment created by the lateral ligament at varus deformities of greater than 10°.

2 year old of normal weight were roughly equivalent. However, increasing varus caused a more rapid accentuation of stress in the medial epiphyseal cartilage for the 5 year old than for the 2 year old, suggesting that smaller degrees of varus are sufficient to cause detrimental changes in the epiphyseal cartilage in the 5 year old. Similarly, higher stresses in the proximal epiphyseal cartilage of the tibia were noted in all cases for the obese 2 and 5 year old compared with the 2 and 5 year old of normal weight. These results suggest that obesity may contribute to tibia vara despite the lack of consensus on this subject in the literature (4,16).

If one assumes from the data of Strobino et al. that 500 lb (2,225 N) applied to a Steinmann pin can cause retardation of the growth of the epiphysis (1,23), an estimate of the stress necessary to stop growth in the epiphysis can be made by making some assumptions. If the cross-sectional area of the Steinmann pin used to apply the stress is assumed to be 5.4 cm^2 (0.21 inches or 0.53 cm in diameter), a stress of 4.12 MPa (600 psi) is determined as the minimum constantly applied stress necessary to shut down the growth of the epiphysis completely. This value appears to be reasonable as it gives a safety factor of approximately two for stresses occurring in the normal proximal epiphyseal cartilage of the tibia in 2 year olds even if obese and in normal 5 year olds. This safety factor would most likely be increased if one considered the average forces present. The 5-year-old child of normal weight with 10° of varus would be borderline at the medial epiphyseal plate for retardation of growth. However, the obese 5 year old would exceed this value and would presumably have a tendency toward tibia vara. The 2-year-old child with varus deformity exceeding 20° would have a tendency for progression based on stresses in the medial epiphysis. A secondary factor which could accentuate the progression of tibia vara in each of these cases is the accompanying tension in the lateral epiphyseal plate.

These observations have at least theoretical application to the clinical treatment of Blount's disease. Weight loss as a modality has a limited application at best. First, the amount of weight necessary to move the 2-year-old child from the 90th to the 50th percentile is 1.5 kg, or 11% of body weight. Second, the resulting decrease in stress would not be sufficient in any but the borderline cases to prevent growth impairment. In this sense obesity has a weak mechanical effect in the 2 year old, in agreement with Levine and Drennan (16). Control of the varus by bracing would appear to be much more effective in reducing the force on the medial epiphysis. To be effective, however, it must be worn at least when up and walking, in contrast to the common clinical practice of night bracing, and be started before physeal damage occurs. This is in agreement with the results of Hoffman et al., who reported a poor final outcome if physeal damage was permitted to occur (13). For example, in an obese 2 year old with 20° varus, with stresses approaching five times normal, but no changes have yet occurred in the epiphysis, prophylactic weight-bearing bracing may have a significant role in treatment.

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