Hip stress reduction after Chiari osteotomy

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Abstract—*A mathematical model was developed to study the effect of the Chiari osteotomy on the distribution of contact hip stress over the weight-bearing area. It was shown that Chiari osteotomy can increase the weight-bearing area directly (on the lateral side), owing to the additional area formed by the* ala ossis ilii *segment, and indirectly (on the medial side), owing to the shift of the stress pole in the medial direction. As a consequence, the contact hip stress is reduced after Chiari osteotomy. The indirect effect is important and often larger than the direct one. Using the proposed mathematical model and standard anteroposterior roentgenographs from archives, the average peak stress on the weight-bearing area, normalised with respect to the body weight (p_{max}/W_B), was determined before and after Chiari osteotomy ($8310\,m^{-2}$ and $4480\,m^{-2}$, respectively) on a population of 29 dysplastic hips. The difference was statistically significant ($p<0.005$). Based on the results presented, it can be concluded that the hip joint contact stress in dysplastic hips considerably decreases after Chiari osteotomy, indicating a favourable biomechanical effect of this operation.*

Keywords—*Chiari osteotomy, Hip joint, Contact stress, Mathematical modelling*

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1 Introduction

The Chiari osteotomy, introduced in the 1950s (Chiari, 1953), was recommended for dysplastic hips, with or without osteoarthritis, for congenital subluxations in young adults, for coxa magna in Perthes disease and for paralytic dislocations caused by muscular weakness and spasticity.

The osteotomy is made just above the hip joint capsule at the anterior inferior iliac spine and extends transversely and upwards to the greater sciatic notch. The lower fragment is moved medially as far as the bony contact will allow. The cut edge of the proximal side of the osteotomy forms an extended roof that is lined by the joint capsule. The capsule remains intact during the operation. The aim of the operation is to improve the acetabular roof, i.e. the covering of the femoral head. Preoperatively elevated contact hip joint stress, indicated as one of the reasons for the development of coxarthrosis (Hadley *et al.*, 1990; Maxian *et al.*, 1995; Iglič *et al.*, 2001), should consequently be reduced.

In general, the choice of whether a patient should undergo a surgical procedure on the hip is based on the clinical and biomechanical state of the patient's hip (Pauwels, 1976; Johnston *et al.*, 1979; Brand, 1997; Brand *et al.*, 2001). By 'biomechanical state', we mean a set of physical quantities such as forces and stresses acting in the hip (Pauwels, 1976; Kummer, 1991; Brand, 1997). The biomechanical state of the hip involves more than the morphological and radiographical state of the hip described by parameters such as trabecular trajectories in the femoral head and neck (Pauwels, 1976), the percentage of coverage of the femoral head (Hefti, 1995) and various geometrical parameters of the hip and pelvis (Wiberg, 1939; Busse *et al.*, 1972; Kersnič *et al.*, 1997; Ganz *et al.*, 1988).

The parameters determined in morphological and radiographic studies were actually introduced to represent the biomechanical state of the hip. To take into account the complex interactions that take place and to develop a more realistic description of the biomechanical state of the hip, mathematical models are used to determine forces and stresses in the hip (Johnston *et al.*, 1979; Iglič *et al.*, 1993*a*; Hipp *et al.*, 1999; Daniel *et al.*, 2001). It has been suggested that assessment of the forces and stresses in the hip using appropriate mathematical models could be used to improve the understanding of the processes leading to development of coxarthrosis, as well as to predict the optimum geometry of the hip after the operation (Pauwels, 1976; Kummer, 1991; Brand,.1997).

The hypothesis was proposed that increasing the coverage of the femoral head in places where it is deficient should decrease the contact stress in the hip joint (Ganz *et al.*, 1988; Millis *et al.*, 1995; Murphy *et al.*, 1999). However, relatively few works addressing changes in the biomechanical state of the hip in a quantitative manner (Iglič *et al.*, 1993*a*; Hipp *et al.*, 1999; Kummer *et al.*, 1991; Zupanc *et al.*, 2001; Vengust *et al.*, 2001) are available to provide a test of this hypothesis.

In the case of the Chiari osteotomy, postoperative changes in the muscle forces (Delp *et al.*, 1990; Iglič *et al.*, 1993*c*) and a postoperative change in the resultant hip joint force

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(IGLIČ *et al.*, 1993*c*; ANTOLIČ *et al.*, 1996) have been predicted. However, a mathematical estimation of the hip contact stress before and after the Chiari osteotomy has not yet been reported to our knowledge. Therefore the specific aim of the present work was to construct a mathematical model for estimating the contact stress distribution and the weight-bearing area in the dysplastic hip joint before and after the Chiari osteotomy, where the additional coverage of the femoral head by the *ala ossis ilii* (CHIARI, 1953) was to be taken into account.

Using the proposed mathematical model for determination of the contact stress distribution, a mathematical model for calculation of the resultant hip joint force in a one-legged stance (IGLIČ *et al.*, 1993*b*; DANIEL *et al.*, 2001) and standard anteroposterior roentgenographs from the archives, the hip joint contact stress distribution was determined before and after the Chiari osteotomy on a population of dysplastic hips.

2 Material and methods

2.1 *Mathematical model of stress distribution in the hip joint after Chiari osteotomy*

In the model, the femoral head is represented by a fraction of a sphere, and the acetabulum is represented by half of a spherical shell, called the acetabular contact hemisphere. An articular surface is imagined, its radius r being the average of the radii of the femoral head and the acetabulum. The shear stresses in the hip joint due to friction are neglected because of the small value of the frictional coefficient of the hip joint articular surface (EBERHARDT *et al.*, 1991; MCCUTCHEN, 1962; LIPSHITZ and GLIMCHER, 1979), so that only the normal stress is considered. We refer to the normal stress as the contact hip joint stress.

When the hip is not loaded, the sphere of the femoral head and the sphere of the acetabulum are considered to be concentric. Upon loading, the centres of both spheres no longer coincide, and the femoral head moves towards the acetabulum, thereby squeezing the intermittent cartilage (BRINCKMANN *et al.*, 1981). The point of closest approach of the two spheres is called the pole of the stress distribution. It is taken that stress in the hip joint articular surface is proportional to strain within the cartilage. Consequently, stress at the chosen point on the articular surface is described as (BRINCKMANN *et al.*, 1981; IGLIČ *et al.*, 1993*a*) $p = p_0 \cos\gamma$, where p_0 is the value of stress at the pole, and γ is the angle between the radius vectors to the pole and the radius vector to the chosen point. In the spherical co-ordinate system, the co-ordinates of the pole are the azimuthal angle Φ and the polar angle Θ. The angle Θ is taken to be positive in the lateral direction. Considering the resultant hip force to be known, the distribution of stress on the hip joint articular surface can be calculated, taking into account the relationship between the contact stress and the resultant hip joint force $\boldsymbol{R}$,

$$\int p_0 \cos\gamma \, d\boldsymbol{A} = \boldsymbol{R} \tag{1}$$

where $d\boldsymbol{A}$ is the area element. The integration is performed over the weight-bearing area A. The lateral border of the weight-bearing area is defined by the lateral coverage of the femoral head. On the medial side, the border is defined by the condition that stress vanishes. This means that the medial border is an angle of $\pi/2$ away from the pole (IPAVEC *et al.*, 1999). The resultant hip joint force can, in general, be expressed by its magnitude and direction.

In this work, we consider the one-legged stance where the resultant hip force lies in the $y = 0$ (frontal) plane (see Fig. 1). Therefore the resultant hip force can be described by only two parameters $\boldsymbol{R} = (-R\sin\vartheta_R, 0, R\cos\vartheta_R)$, where R is the magnitude of the resultant hip force, and ϑ_R determines the angular displacement of the resultant hip force from the vertical axis, as defined in Fig. 1. The angle ϑ_R is taken to be positive for the inclination of $\boldsymbol{R}$ that is presented schematically in Fig. 1. In the following, the co-ordinate system is rotated, so that $\sin\Phi = 0$ and $\Theta = 0$ (IPAVEC *et al.*, 1999). In the rotated system, the resultant hip force is

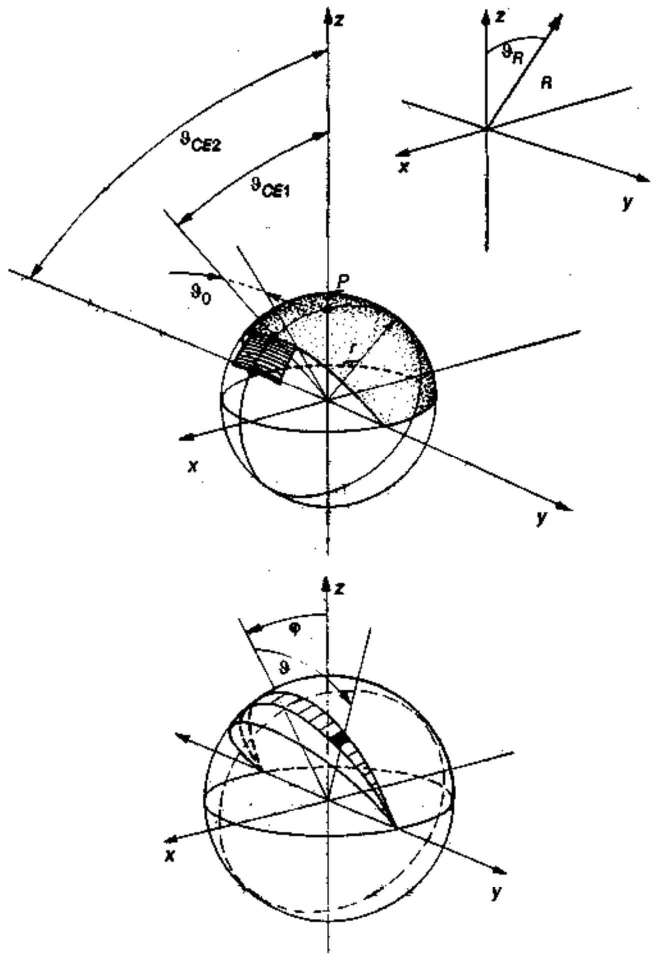

Fig. 1 *Schematic representation of hip joint articular surface after Chiari osteotomy (above).* ( ) *weight-bearing area of* ala ossis ilii *osteotomy segment;* ( ) *weight-bearing area of acetabulum. Centre edge angles ϑ_{CE1} and ϑ_{CE2} and angle ϑ_0, representing width of* ala ossis ilii *osteotomy segment, are indicated. Resultant hip force is depicted (upper right). P and r denote pole and radius of articular sphere, respectively. Definitions of angles ϑ and φ are given*

$$\boldsymbol{R} = (-R\sin(\vartheta_R + \Theta), 0, R\cos(\vartheta_R + \Theta)) \tag{2}$$

To express the integrals of (1), we have, in the previous works (IGLIČ *et al.*, 1993*a*; IPAVEC *et al.*, 1999), used spherical co-ordinates. Here, we introduce a somewhat different choice of co-ordinates that proves to be more convenient for the modelling of the additional acetabular roof (Fig. 1). The chosen co-ordinates are $x = r\cos\vartheta\sin\varphi$, $y = r\sin\vartheta$ and $z = r\cos\vartheta\cos\varphi$, where r is the radius of the articular sphere, and the angles ϑ and φ are depicted in Fig. 1. The angle φ is considered to be positive in the lateral direction and negative in the medial direction (Fig. 1). The area element is

$$d\boldsymbol{A} = r^2\cos\vartheta(\cos\vartheta\sin\varphi, \sin\vartheta, \cos\vartheta\cos\varphi)d\varphi\, d\vartheta \tag{3}$$

and

$$\cos\gamma = \cos\vartheta\cos\varphi \tag{4}$$

Using expressions (1), (3) and (4), the components of the force $\boldsymbol{R}$ are

$$R_x = p_0 r^2 \int \cos^3 \vartheta \, d\vartheta \int \cos\varphi \sin\varphi \, d\varphi \tag{5}$$

$$R_y = p_0 r^2 \int \cos^2 \vartheta \sin\vartheta \, d\vartheta \int \cos\varphi \, d\varphi \tag{6}$$

$$R_z = p_0 r^2 \int \cos^3 \vartheta \, d\vartheta \int \cos^2 \varphi \, d\varphi \tag{7}$$

The integration is performed over the weight-bearing area. The weight-bearing area is divided into two parts (Fig. 1). The first part is formed by the *ala ossis ilii* segment. For simplicity, we assume that the roof is symmetric with respect to the $y = 0$ plane and that the pole lies on the lateral side of the acetabular contact hemisphere. This can be expected for the one-legged stance position of the body. Therefore the integration bounds are $\vartheta \in (-\vartheta_0, \vartheta_0)$ and $\varphi \in (\vartheta_{CE1} - \Theta, \vartheta_{CE2} - \Theta)$. The angles ϑ_{CE1} and ϑ_{CE2} and Θ are taken to be positive in the lateral direction. The meaning of the angles ϑ_0, ϑ_{CE1} and ϑ_{CE2} can be deduced from Fig. 1. The second part is formed by the acetabular shell. The integration bounds are $\vartheta \in (-\pi/2, \pi/2)$ and $\varphi \in (-\pi/2, \vartheta_{CE1} - \Theta)$. After some calculation, we obtain

$$R_x = -p_0 r^2 g \tag{8}$$

$$R_y = 0 \tag{9}$$

$$R_z = p_0 r^2 h \tag{10}$$

where

$$g = \frac{2}{3}\cos^2(\vartheta_{CE1} - \Theta) + \left(\sin\vartheta_0 - \frac{\sin^3\vartheta_0}{3}\right) \times (\cos^2(\vartheta_{CE2} - \Theta) - \cos^2(\vartheta_{CE1} - \Theta)) \tag{11}$$

$$h = \frac{2(\vartheta_{CE1} - \Theta + \pi/2 + \sin(2(\vartheta_{CE1} - \Theta))/2)}{3} + \left(\sin\vartheta_0 - \frac{\sin^3\vartheta_0}{3}\right)\left(\vartheta_{CE2} - \vartheta_{CE1} + \frac{\sin(2(\vartheta_{CE2} - \Theta))}{2} - \frac{\sin(2(\vartheta_{CE1} - \Theta))}{2}\right) \tag{12}$$

Using the expressions for the components of the resultant hip force (2) and (8) and (10)–(12), the co-ordinate of the stress pole Θ is determined from the non-linear algebraic equation

$$tg(\vartheta_R + \Theta) - \frac{g}{h} = 0 \tag{13}$$

The value of stress at the pole p_0 can then be obtained from (8):

$$p_0 = R\cos(\vartheta_R + \Theta) r^{-2} \Bigg/ \left(\frac{2(\vartheta_{CE1} - \Theta + \pi/2 + \frac{1}{2}\sin(2(\vartheta_{CE1} - \Theta)))}{3} + \left(\sin\vartheta_0 - \frac{\sin^3\vartheta_0}{3}\right) \times \left(\vartheta_{CE2} - \vartheta_{CE1} + \frac{\sin(2(\vartheta_{CE2} - \Theta))}{2} - \frac{\sin(2(\vartheta_{CE1} - \Theta))}{2}\right)\right) \tag{14}$$

The unique solution of the non-linear equation (13) was found numerically using the Newton iterative method. The value of ϑ_0 (Fig. 1) was estimated to be between 10° and 40°, according to the thickness of the *ala ossis ilii* at the cut. If we take $\vartheta_0 = 0$, we recover the equations of the model (IPAVEC *et al.*, 1999) for the centre–edge angle $\vartheta_{CE} = \vartheta_{CE1}$, and, for $\vartheta_0 = 90°$, we recover the equations of the model (IPAVEC *et al.*, 1999) for $\vartheta_{CE} = \vartheta_{CE2}$.

We describe the hip joint stress by its maximum value on the weight-bearing area p_{max}. If the pole of the stress distribution lies within this area, p_{max} is equal to p_0. If the pole lies outside the weight-bearing area, the value of maximum stress is taken at the point closest to the pole (BRINCKMANN *et al.*, 1981; IPAVEC *et al.*, 1999).

To determine the stress distribution in a non-operated hip, the magnitude and the direction of the resultant hip joint force, the radius of the articular sphere and the Wiberg angle should be known, whereas, to determine the stress distribution after the Chiari osteotomy, the magnitude and the direction of the resultant hip force, the radius of the articular sphere and both centre–edge angles should be known.

2.2 *Determination of hip stress from standard anteroposterior radiograph*

As stated above, the model for determination of hip stress distribution requires as an input the magnitude and the direction of the resultant hip joint force, as well as the radius of the articular sphere and the centre–edge angles. The radius of the articular sphere r and the centre–edge angles before and after the operation (ϑ_{CE1} and ϑ_{CE2}, respectively) were determined from the standard anteroposterior roentgenograph (Fig. 2). The radius of the articular sphere was estimated by the radius of the femoral head.

The resultant hip joint force was determined using a three-dimensional mathematical model of an adult human hip in a one-legged stance (IGLIČ *et al.*, 1993*b*; DANIEL *et al.*, 2001). It was found that, in the one-legged stance, the resultant hip force lies almost in the frontal plane of the body (IGLIČ *et al.*, 1993*b*). The model for determination of the resultant hip force requires as input additional geometrical parameters of the pelvis and the proximal femur (Fig. 2): the inter-hip distance l, the pelvis height H, the pelvis width C, the vertical and horizontal co-ordinates of the effective muscle attachment point on the greater trochanter v_T and h_T, respectively, and the body weight W_B.

The geometrical parameters were obtained from digitised profiles of the roentgenographs using the HIJOMO program (ZUPANC *et al.*, 2001; KERSNIČ *et al.*, 1997). The HIJOMO program was adjusted for the purpose of this work by also considering the centre–edge angle after Chiari osteotomy (ϑ_{CE2}).

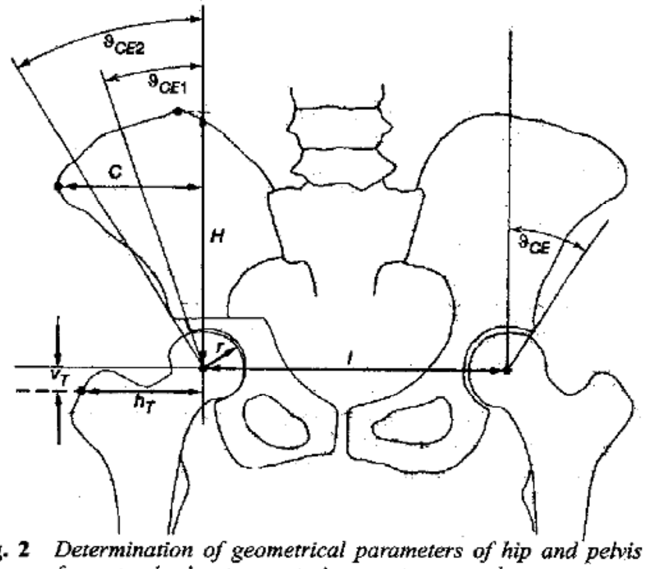

Fig. 2 *Determination of geometrical parameters of hip and pelvis from standard anteroposterior roentgenograph*

In non-operated hips, stress distribution was determined by the HIPSTRESS program, as described in detail elsewhere (DANIEL *et al.*, 2001; ZUPANC *et al.*, 2001; VENGUST *et al.*, 2001).

2.3 *Roentgenographs*

Standard anteroposterior roentgenographs of adult patients who underwent Chiari pelvic osteotomy at the Department of Orthopaedic Surgery in Ljubljana, in the period from 1980 to 1990, were taken from the archive. The roentgenographs of 29 female patients were considered in this study. The average age at the time of operation was 31.9 years (range 18–51 years). The average time duration between the operation and the control, when the second roentgenograph was taken, was 2.7 years.

For comparison, 29 roentgenographs of healthy female hips were taken from the archive of the Clinical Department of Traumatology in Ljubljana. These roentgenographs were made within the standard procedure for treatment of injured patients. The average age of the patients was 31.0 years (range 18–51).

In all roentgenographs, an average magnification of 110% was taken into account. The data were analysed by descriptive statistical methods. The distributions of all the variables were normal, and therefore average values of the respective groups could be compared.

3 Results

The effect of the Chiari osteotomy on the distribution of the contact hip stress was studied theoretically using the developed mathematical model, in which the additional coverage of the femoral head by the *ala ossis ilii* could be taken into account.

Fig. 3 shows the calculated peak stress on the weight-bearing area p_{max} for different centre–edge angles ϑ_{CE2} after the operation. For comparison, we show the peak stress on the intact hip joint with the corresponding centre–edge angle $\vartheta_{CE} = \vartheta_{CE2}$. It can be seen that the peak stress is considerably reduced, owing to

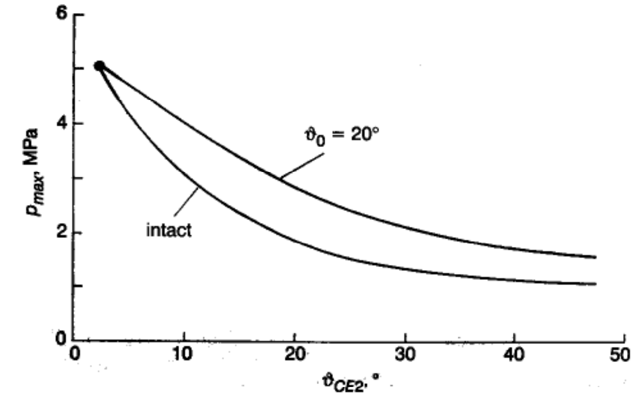

Fig. 3 *Peak stress on weight-bearing area p_{max} as function of centre–edge angle ϑ_{CE2} after Chiari osteotomy for hip with pre-operative centre–edge angle $\vartheta_{CE1} = 2°$. For comparison, corresponding curve for intact hip with centre–edge angle $\vartheta_{CE} = \vartheta_{CE2}$ is also presented. Values of model parameters are $R/W_b = 2.6$, $W_b = 600\,N$, $\vartheta_R = 10°$, $r = 2.7\,cm$, $\vartheta_0 = 20°$*

the Chiari osteotomy, the effect being more significant for larger ϑ_{CE2}. However, the peak stress is still higher than the corresponding peak stress in the intact hip.

Fig. 4 shows the contact stress distribution for different centre–edge angles ϑ_{CE2} after the operation. For comparison, we also show the contact stress distribution on the intact hip joint with the corresponding centre–edge angle ϑ_{CE}. The position of the pole is indicated (see black dot). It can be seen that the contact stress considerably decreases after the Chiari osteotomy; however, it is still higher than the corresponding contact stress in the intact hip, with $\vartheta_{CE} = \vartheta_{CE2}$. The effect is more significant for larger values of ϑ_{CE2} , i.e. for a larger additional acetabular roof formed by the *ala ossis ilii* segment (see also Fig. 1).

Fig. 5 shows the size of the weight-bearing area A for different centre–edge angles ϑ_{CE2} after the operation. The individual contributions, i.e. the contribution of the *ala ossis ilii* osteomy segment A_{roof} and the contribution of the acetabulum A_{acet} are

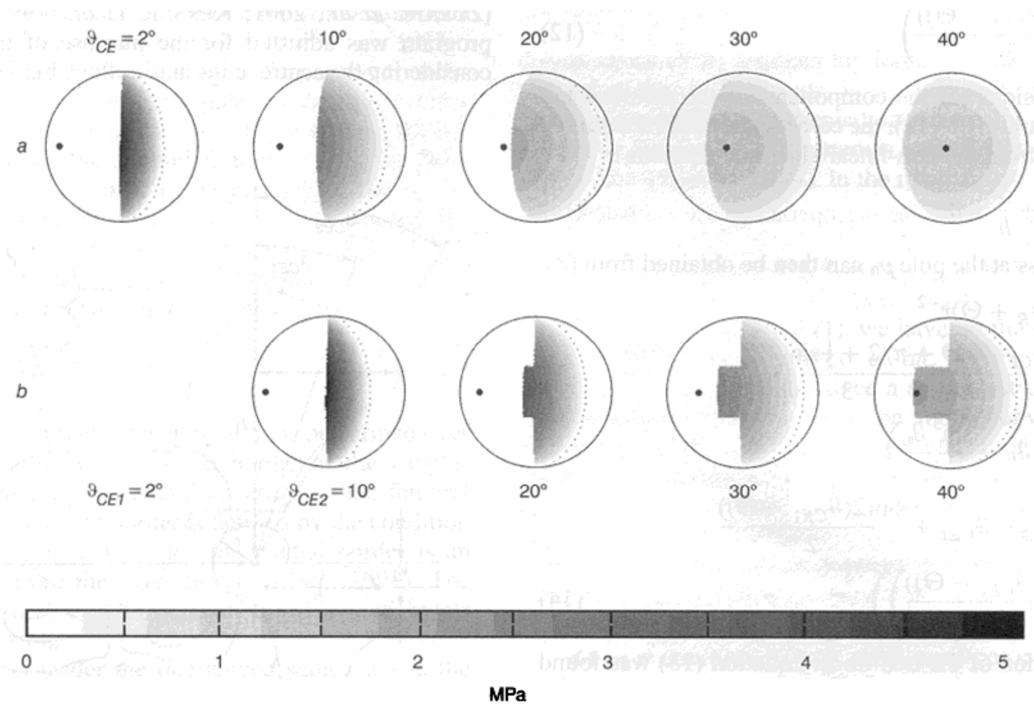

Fig. 4 *(a) Stress distributions in hips with different centre–edge angles ϑ_{CE} as indicated. (b) Stress distributions after Chiari osteotomy for pre-operative centre–edge angle $\vartheta_{CE1} = 2°$ and different postoperative centre–edge angles ϑ_{CE2}. View from top is given, and position of pole is marked. Values of model parameters are as given in Fig. 3*

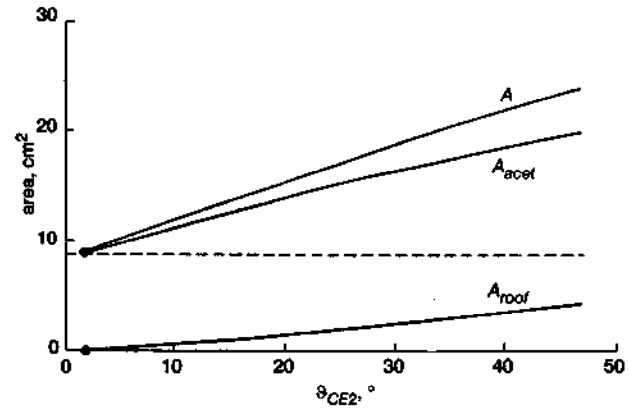

Fig. 5 *Size of weight-bearing area A as function of postoperative centre–edge angle ϑ_{CE2} for pre-operative centre–edge angle $\vartheta_{CE1} = 2°$. Both contributions to area A are depicted: contribution of* ala ossis ilii *osteotomy segment A_{roof} and contribution of acetabulum A_{acet}. (- - -) value of weight-bearing area before operation. Values of model parameters are as given in Fig. 3*

also given. It can be seen that the operation significantly increases the weight-bearing area in the medial region of the acetabulum. This indirect contribution to the increase in the weight-bearing area A_{acet} is several times larger (for example, four times at $\vartheta_{CE2} = 20°$) than the direct one A_{roof} and, for larger ϑ_{CE2}, exceeds even the size of the weight-bearing area before the operation.

Fig. 6 shows the effect of the width of the additional femoral roof (determined by the angle ϑ_0) on the peak stress p_{max}. The value of $\vartheta_0 = 90°$ is the limit of the intact hip ($\vartheta_{CE} = \vartheta_{CE2}$).

By using the methods described above, we determined the relevant geometrical parameters, the magnitude and the inclination of the resultant hip force, the peak stress and the weight-bearing area for 29 hips that underwent the Chiari operation. We also determined the corresponding quantities for 29 healthy hips. As there were no data on the weight of the patients, we present the peak stress normalised by the body weight. The results are shown in Table 1.

The normalised resultant hip force R/W_B on average is 3.14 (SD = 0.26) before the operation, 3.18 (SD = 0.39) after the operation and 2.71 (SD = 0.17) in normal hips. There is no statistically significant difference between the values of R/W_B, before and after the operation ($p = 0.64$), whereas the differences between the group of normal hips and both groups of operated hips (before and after the operation) are statistically significant ($p < 0.005$).

Analysis of the roentgenographs showed that the Chiari osteotomy considerably and statistically significantly decreases

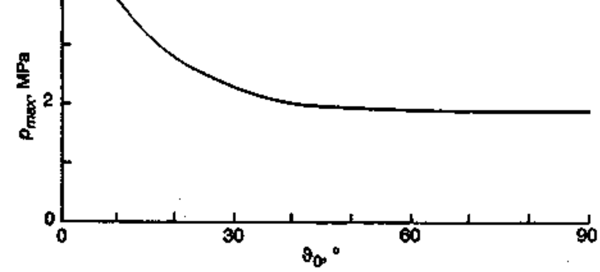

Fig. 6 *Peak stress p_{max} as function of width of additional femoral roof ϑ_0. Values of model parameters are $R/W_b = 2.6$, $W_b = 600\,N$, $\vartheta_R = 10°$, $r = 2.7\,cm$, $\vartheta_{CE1} = 2°$, $\vartheta_{CE2} = 20°$*

Table 1 Biomechanical parameters: resultant hip force normalised with respect to body weight R/W_B, peak stress on weight-bearing area normalised with respect to body weight p_{max}/W_B and weight-bearing area A for hips before and after Chiari osteotomy, and for normal hips, as determined by mathematical models. Standard deviations are given in parentheses

	Before operation	After operation	Normal
R/W_B	3.14 (0.26)	3.18 (0.39)	2.71 (0.17)
p_{max}/W_B, m^{-2}	8310 (4021)	4480 (2575)	3540 (845)
A, cm^2	12.63 (5.00)	20.31 (6.69)	19.40 (3.65)

the normalised peak stress p_{max}/W_B. However, the average normalised peak stress after the operation is higher than the average normalised peak stress in the population of normal hips. The normalised peak stress p_{max}/W_B, on average, is $8310\,m^{-2}$ (SD = $4021\,m^{-2}$) before the operation, $4480\,m^{-2}$ (SD = $2575\,m^{-2}$) after the operation and $3540\,m^{-2}$ (SD = $845\,m^{-2}$) in normal hips (Table 1). The difference between the groups before and after the operation is statistically significant ($p < 0.005$), whereas the difference between the group after the operation and the group of normal hips is not statistically significant ($p = 0.07$).

The size of the weight-bearing area A on average, is $12.63\,cm^2$ (SD = $5.00\,cm^2$) before the operation, $20.31\,cm^2$ (SD = $6.69\,cm^2$) after the operation and $19.40\,cm^2$ (SD = $3.65\,cm^2$) in normal hips. The difference between the groups before and after the operation is statistically significant ($p < 0.005$), whereas the difference between the group after the operation and the group of normal hips is not statistically significant ($p = 0.5$).

4 Discussion

The hypothesis was tested that increasing the operative coverage of the femoral head where it is deficient should decrease the contact stress in the hip joint. By calculating the contact stress distribution of the hip before and after the Chiari osteotomy, in the present work, we provide evidence in favour of this hypothesis. Favourable clinical results have also been reported (MIGAUT *et al.*, 1995; NISHINA *et al.*, 1990; OSEBOLD *et al.*, 1997; REYNOLDS, 1986; WINDHAGER *et al.*, 1991) in accordance with this hypothesis.

Our theoretical results presented in Figs 4 and 5 indicate that the Chiari osteotomy increases the weight-bearing area directly, owing to additional coverage by the *ala ossis ilii*, and indirectly, owing to an increase in the weight-bearing area on the medial side. The indirect effect occurs owing to the shift of the stress pole in the medial direction. The increase in the weight-bearing area due to the shift of the stress pole in the medial direction is represented in Fig. 5 by the difference between A_{acet} and the initial A (broken line).

It can be seen in Fig. 6 that the wider roof reduces the stress more effectively; however, the effect exhibits saturation, so that values of ϑ_0 higher than about 30° bring no significant additional improvement. This is owing to low values of stress at the edge of the weight-bearing area far from the pole.

The indirect effect of the Chiari osteotomy in increasing the weight-bearing area is even more important than the direct effect, as it causes the relief of stress at those parts of the weight-bearing area where the stress is the highest before the operation (Fig. 4). Besides lowering values of the stress in these regions of the weight-bearing area, the gradient of contact stress on the lateral border is also decreased. This may be of importance as the contact stress gradients are related to fluid flow in the articular cartilage and may therefore directly influence tissue remodelling (BRAND, 1997).

HIPP *et al.* (1999) estimated the weight-bearing area for dysplastic hips and for normal hips. The weight-bearing area was obtained as a portion of the sphere that lies within the edges defined by the digitalisation of the acetabular rim and the acetabular notch. A three-dimensional reconstruction of the acetabulum and femur was obtained from computed tomographic data. They found that the average weight-bearing area was about 13 cm^2 in dysplastic hips, which is in agreement with our results, and about 18 cm^2 in normal hips, which is smaller than our value (Table 1). However, in our sample of normal hips, the average centre–edge angle was somewhat larger (35°) than in the sample of HIPP *et al.* (32°), and this can be considered to be the reason for the differences observed between the values of the weight-bearing area of normal hips.

We took into account that the size of the weight-bearing area at a given body position is consistently related to the stress distribution and is not simply a morphological parameter. The stress distribution and the size of the weight-bearing area are different in different body positions and activities. In this work, we analysed (Figs 3–6) the peak stress and the size of the weight-bearing area for a given magnitude and direction of the resultant hip force. The analysis could be further upgraded by considering that the magnitude and the direction of the resultant hip force change with time, for example during gait (BRAND *et al.*, 1994; PEDERSEN *et al.*, 1997; IPAVEC *et al.*, 1999). However, during gait, the effective centre–edge angle, if measured in the laboratory co-ordinate system, changes owing to swinging of the pelvis. For reasons of simplicity, the contact stress distribution was therefore calculated in the pelvic co-ordinate system, where the contact stress distribution represents the loading of the acetabulum (IPAVEC *et al.*, 1999).

For the purpose of this study, we adjusted the HIJOMO computer program for determination of the geometrical parameters (ZUPANC *et al.*, 2001; KERSNIČ *et al.*, 1997) by determining an additional centre–edge angle. There are still unresolved problems with the precision of the determination of the radius of the femoral head. The program fits the profile of the femoral head by a circle using the least squares method. However, the heads of dysplastic hips can deviate considerably from the spherical. It seems that the radius of the articular sphere is somewhat underestimated, as the head of the dysplastic hip is flattened, and therefore, in effect, the distance to the centre of rotation is increased.

Although this biomechanical study was inspired by the Chiari osteotomy, the main result regarding the augmentation of the weight-bearing area due to the shift of the stress pole can be generalised to any hip osteotomy that affects the stress distribution. It is shown in this work that a small increase in the weight-bearing area in the region of high stress can cause a considerable shift of the stress pole and therefore a change in stress distribution. This causes an increase in the weight-bearing area that can be several times larger than the direct increase in the weight-bearing area.

There may be an additional effect of the Chiari osteotomy due to the medial or lateral shift of the femoral head centre (JOHNSTON *et al.*, 1979; IGLIČ *et al.*, 1993*c*; DELP *et al.*, 1990). It was suggested (ANTOLIČ *et al.*, 1996) that it is favourable if the femoral head centre is moved medially, as, in this way, the resultant hip force (JOHNSTON *et al.*, 1979; SRAKAR *et al.*, 1992; IGLIČ *et al.*, 1993*c*) and the hip contact stress (IGLIČ *et al.*, 1993*a*) can be substantially reduced. The present clinical study indicates that there is no change, on average, in the magnitude of the resultant hip force after the operation. This is in agreement with previous measurements, where no average shift of the interhip distance could be found (ANTOLIČ *et al.*, 1996).

The Chiari osteotomy can also cause a shift of some muscle attachment points. Therefore the length of the muscles and the maximum available muscle forces can change after the operation (DELP *et al.*, 1990; IGLIČ *et al.*, 1993*c*).

During the stance phase of slow gait, the accelerations are not significant (MCLEISH and CHARNLEY, 1970), and the vertical floor reaction force is nearly constant for a period (CHARNLEY and PUSSO, 1968). Therefore the one-legged stance is important, not only in its own right, but also owing to its resemblance to the stance phase of slow gait (MCLEISH and CHARNLEY, 1970). In addition, it was also indicated that the peak hip stress during the midstance phase of gait is related linearly to peak hip stresses in all phases of gait, as well as to some other activities such as adduction, external rotation and flexion (HIPP *et al.*, 1999). Therefore, in the present clinical study, the distribution of the contact hip stress was calculated in the static one-legged stance, which is considered to be a representative body position. For this body position, the geometrical parameters required as input data for the mathematical models described can be estimated from standard anteroposterior roentgenographs (DANIEL *et al.*, 1999), which can be taken from the archives. No additional measurements on patients are therefore required.

5 Conclusions

In this paper, the effect of the Chiari osteotomy on the distribution of the contact hip stress was studied using a mathematical model. It was shown that the Chiari osteotomy can substantially increase the weight-bearing area and, consequently, decrease the contact stress in the hip joint. Based on the present theoretical study, it was concluded that the Chiari osteotomy can increase the weight-bearing area directly, owing to the additional area formed by the *ala ossis ilii* segment, and indirectly, owing to the shift of the stress pole in the medial direction. The indirect effect is important and usually larger than the direct one. Using the proposed mathematical model and standard anteroposterior roentgenographs from the archives, it was also shown on a population of 29 dysplastic hips that the contact stress considerably decreases after the Chiari osteotomy.

In conclusion, our results indicate that the redistribution of stress after Chiari osteotomy can yield biomechanically favourable effects, so that the biomechanical state of the hip approaches the situation in the normal hip. From this point of view, the Chiari hip osteotomy is a successful solution and should be considered as a possibility for preserving the patient's own hip as long as possible (BRAND, 1997; MILLIS *et al.*, 1995).

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