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ORIGINAL ARTICLE

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Biomechanical evaluation of hip joint after Salter innominate osteotomy: a long-term follow-up study

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Abstract The biomechanical state of the hip after a Salter innominate osteotomy was investigated by using the radiographic data of 38 operated and 21 contralateral nonoperated hips from our archives. The centre-edge angle of Wiberg was determined from the radiographs taken shortly after the operation. From the radiographs of the latest follow-up (7–13 years after the operation), we also determined the peak value of contact hip joint stress normalized by the body weight, and the functional angle of the weight-bearing area. A mathematical model was used. We show that the geometrical parameters aside from the centre-edge angle may considerably influence the contact hip stress distribution. We also show that the functional angle of the weight-bearing area is a more relevant parameter than the normalized peak stress if the exact magnification of the images is not known and if there is considerable variation of the image size within the sample. The development of the centre-edge angle of the operated hips and of the contralateral hips was also studied. We found that the centre-edge angle increases on average during the follow-up time in the operated hips as well as in the contralateral nonoperated hips, but the average increase is smaller in the former. It is shown that an unfavorable stress distribution is connected to the decrease of the centre-edge angle over time. Finally, we found a weak positive correlation between the centre-edge angle shortly after the operation and the functional angle of the weight-bearing area at the of the latest follow-up.

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Introduction

It was suggested that too high hip joint contact stress due to a small weight-bearing area is an important factor accelerating the development of coxarthrosis [10, 15, 26]. Salter innominate osteotomy [31] is one of the operative procedures that is indicated in developmental dysplasia of the hip in order to establish a larger weight-bearing area and consequently lower stress. If the operation is performed at an early age, the changed pelvis geometry and consequently the changed biomechanical state of the hip importantly influence the transformation from an immature to an adult hip [33].

Knowing the biomechanical state of the hip involves more than morphological studies as it may give insight into the development of the hip. It is acknowledged that the biomechanical state of the hip can be estimated by the centre-edge angle of Wiberg ϑ_{CE} [35] and also by some other geometrical parameters of the hip and pelvis [5], as for example the acetabular angle of Sharp [32] and the percentage of the coverage of the femoral head [14, 21, 27]. However, these parameters were introduced to represent physical quantities such as forces and stresses in the hip joint and the size of the weight-bearing area. In order to take into account the complex interactions that are taking place and pursue a more realistic description, a relevant mathematical model that directly gives these quantities (forces, stresses and the size of the weight-bearing area) and also enables study of the influence of individual geometrical parameters on them could be of use in predicting an optimal configuration of the hip and pelvis after the operation.

First, the mathematical models and the corresponding computer programs for individual patients were made to calculate the resultant hip force [11, 12, 13]. Based on previous work [1, 28, 29, 30], Legal and co-workers developed a practical method for calculation of the contact

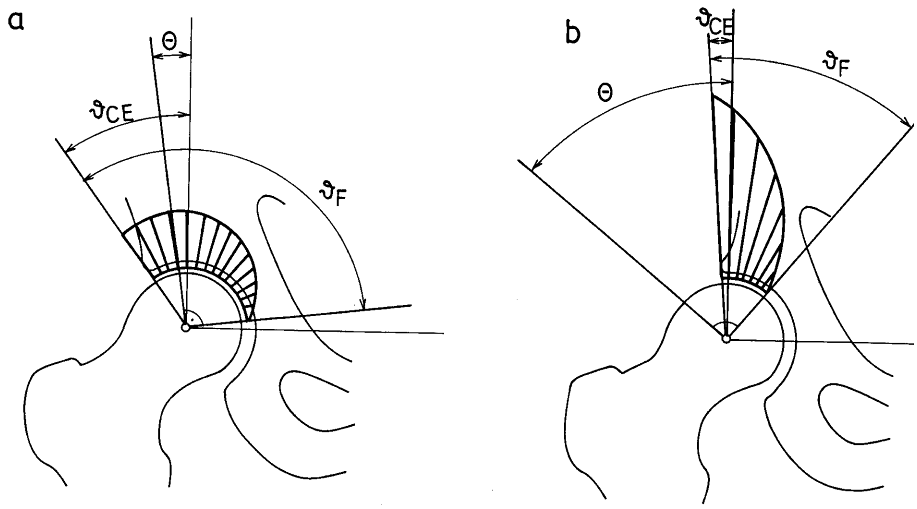

Fig. 1 a, b The scheme of the contact hip joint stress distribution on the weight-bearing area for a normal hip (**a**) and for a dysplastic hip (**b**). The centre-edge angle ϑ_{CE}, the coordinate of the pole θ and the functional angle of the weight-bearing area ϑ_F are indicated

hip joint stress distribution for a specific case [22, 23, 24, 25]. Later, various other mathematical methods for estimation of the contact hip joint stress distribution from the radiographic data were also presented [2, 4, 9, 15, 18].

In this work, we use the evaluation of both the biomechanical state of the hip by the centre-edge angle of Wiberg and a combination of two simple mathematical models: the model for calculation of the resultant hip force in the one-legged stance [17] and the model for determination of the contact hip joint stress distribution [16, 18, 19]. The input parameters of these two mathematical models are the geometrical parameters of the pelvis and the proximal femurs [16, 20] that can be obtained from standard anteroposterior rentgenographs available from the archives.

The specific aims of the presented work were to introduce the functional angle of the weight-bearing area as a biomechanical parameter, to outline the importance of the geometrical parameters aside from the acknowledged centre-edge angle of Wiberg for the hip joint stress distribution, to study the development of the hip geometry in the period after the operation compared to the development of the nonoperated hip, and to study the correlation between the postoperative geometry of the hip and the hip stress in the long-term follow-up.

Theory

We give a brief description of the relevant parameters that are obtained from the mathematical models. A detailed description of the assumptions and derivations is given elsewhere [16, 17, 18, 19]. Within this description, it is assumed that when unloaded, the acetabular shell and the femoral head have a spherical shape with coinciding centres of both spheres. Upon loading, the intermittent cartilage layer is squeezed. The contact hip stress is proposed to be proportional to strain in the cartilage layer [4, 19]. The point of the closest approach of the spherical surfaces of the acetabulum and the femoral head is called the stress pole [4, 18]. An articular sphere is imagined, with the weight-bearing area extending over a part of this sphere. Within the model for calculation of the resultant hip joint force used in this work, the resultant hip force lies in the frontal plane of the body while stress changes over the weight-bearing area according to the cosine function, $p = p_0 \cos(\vartheta - \theta)$ (Fig. 1), where ϑ is the polar coordinate of the observed point, and θ is the polar coordinate of the stress pole. The weight-bearing area is bounded on the lateral side by the acetabular coverage (the centre-edge angle ϑ_{CE}) and on the medial side by the condition of vanishing stress (this means that the medial border of the weight-bearing area lies $\pi/2$ away from the pole (Fig. 1)). Therefore, the weight-bearing area is not simply a morphological parameter but depends also on the body position, which in turn influences the magnitude and the direction of the resultant hip force.

In dysplastic hips, the pole may lie laterally or even outside the weight-bearing area (Fig. 1 b). In such a case, stress decreases steeply on the lateral border (Fig. 1 b), i.e. the gradient of stress is high while the weight-bearing area is small. This is unfavourable since large values of contact hip joint stress combined with large values of its gradient may accelerate the development of coxarthrosis [3].

The biomechanical parameters used in this work are the maximal value of stress on the weight-bearing area normalized with respect to the body weight p_{max}/W_B [4] and the functional angle of the weight-bearing area ϑ_F (Fig. 1), which is defined as

$$\vartheta_F = \pi/2 + \vartheta_{CE} - \theta \qquad (1)$$

The parameter ϑ_F is actually the size of the weight-bearing area A divided by the square of the radius of the articular surface r^2, $A = \vartheta_F\, r^2$.

Low p_{max}/W_B and large ϑ_F are biomechanically favourable, while high p_{max}/W_B and small ϑ_F are biomechanically unfavourable.

Patients and methods

At the Department of Orthopaedic Surgery, Ljubljana, 63 patients (70 hips) underwent Salter osteotomy due to developmental dys-

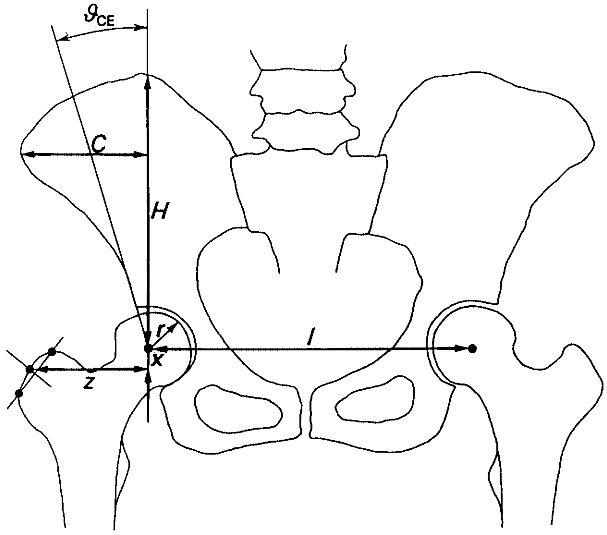

Fig. 2 The geometrical parameters of the pelvis and the proximal femurs that are needed as input data for the mathematical models for calculation of the resultant hip force and the stress distribution that are used in this work

plasia of the hip in the period from 1974 to 1983. Forty-four hips met our enrolment criteria, which included: (a) no radiographic signs of aseptic necrosis or chondrolysis of the femoral head preoperatively and postoperatively, (b) anteroposterior radiographs of the pelvis and both proximal femurs available after the operation, (c) no operation on the hip in the follow-up period.

The mean age of the patients at the time of surgery was 54 months (range 18 months to 10 years), while at the latest follow-up it was 14 years (range 9–23 years).

The centre-edge angle of Wiberg ϑ_{CE} was determined from the radiographs shortly after the Salter osteotomy, once in the course of the 1st postoperative year, once in the 2nd or the 3rd postoperative year, once 3–7 years postoperatively and once 7–13 years postoperatively. We included only those patients with a follow-up period lasting at least 7 years.

Our final sample of the operated hips consists of 38 hips, while our final sample of the contralateral nonoperated hips consists of 21 hips that fulfilled all of the above criteria. The operation was performed on one hip in 32 patients and on both hips in 3 patients.

To determine the contact stress distribution on the weight-bearing area, we used the computer program HIPSTRESS [16]. The program is based on a three-dimensional mathematical model for determination of the resultant hip force in the one-legged stance [17] and on the mathematical model for determination of the contact stress distribution on the weight-bearing area [18, 19]. The mathematical model for determination of the resultant hip force [17] needs as input data the following geometrical parameters of the pelvis and the proximal femurs (Fig. 2): the distance between the centres of the femoral heads l, the coordinates of the effective muscle attachment point on the greater trochanter (z and x, respectively), the vertical distance between the centre of the femoral head and the highest point on the crista iliaca H, the horizontal distance between the centre of the femoral head and the most lateral point on the crista iliaca C and the body weight W_B. The required geometrical parameters can be obtained from standard anteroposterior radiographs of the pelvis and both proximal femurs and are used to scale the reference muscle attachment points [7]. The mathematical model for the determination of the stress distribution on the weight-bearing area [18, 19] needs as input data the magnitude R and the direction ϑ_R of the resultant hip force, the radius of the femoral head r and the centre-edge angle of Wiberg ϑ_{CE} (Fig. 2). The radius of the femoral head was taken as the radius of the articular sphere. The geometrical parameters were obtained from standard anteroposterior radiographs taken at the latest follow-up. An average magnification of 10% was taken into account.

The data were analyzed by the descriptive statistical methods and expressed by the average values, correlation coefficients and the t-test probability.

Results

First we present the biomechanical parameters obtained from the radiographs taken at the time of the latest follow-up. Figure 3 shows the correlation between the centre-edge angle and the normalized peak contact hip joint stress p_{max}/W_B, both determined from the radiograph of the latest follow-up. The normalized peak contact hip joint p_{max}/W_B is described by an exponential trial function, as the theoretical prediction obtained numerically increases steeply with decreasing ϑ_{CE} [19]. There is a negative, statistically significant correlation between p_{max}/W_B and ϑ_{CE} (R^2 = 0.36).

Figure 4 shows the correlation between the centre-edge angle ϑ_{CE} and the functional angle of the weight-bearing area ϑ_F, both determined from the radiographs of the latest follow-up. There is a positive, statistically significant correlation between ϑ_F and ϑ_{CE} (R^2 = 0.93).

Scattering of the data in Figs. 3 and 4 shows that in determining p_{max}/W_B and ϑ_F the parameters other than ϑ_{CE} are also important. It can, however, be seen that scattering of the data is larger for p_{max}/W_B than for ϑ_F, which is reflected also in the respective correlation coefficients. As the patients differed considerably in age at the latest follow-up (range 9–23 years), the geometrical parameters obtained from the radiograph images and consequently p_{max}/W_B reflect these differences in size. On the other

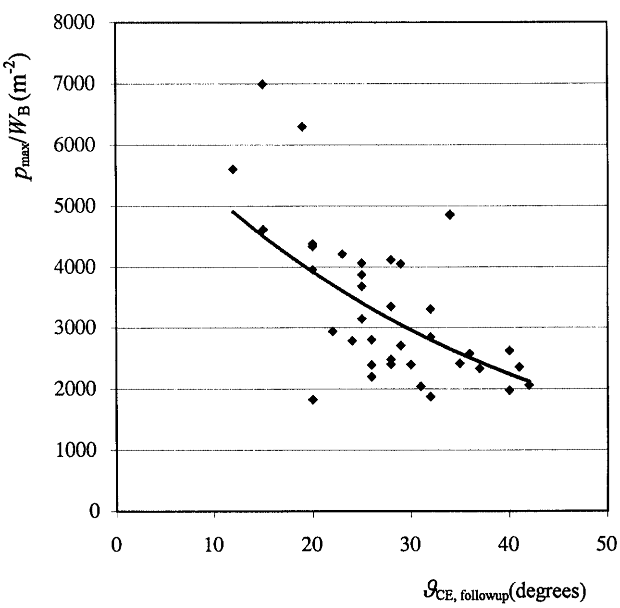

Fig. 3 The correlation between the centre-edge angle ϑ_{CE} and the normalized peak contact hip joint stress p_{max}/W_B, both determined from the radiographs of the latest follow-up. The negative correlation is statistically significant (R^2 = 0.36)

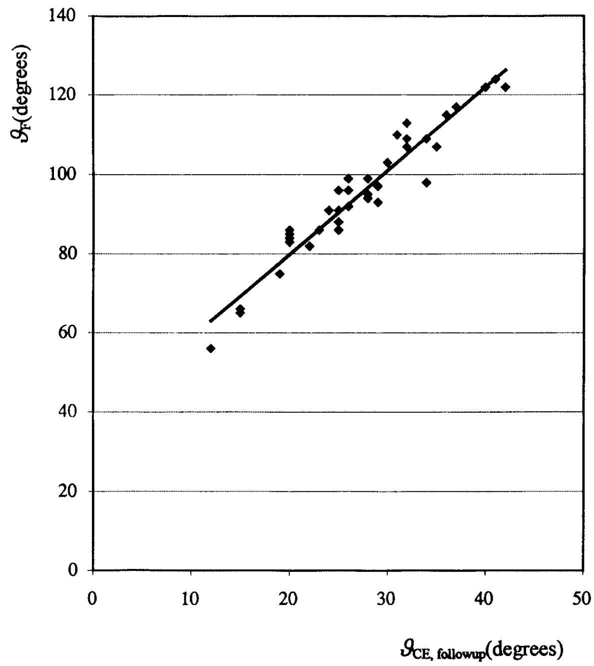

Fig. 4 The correlation between the centre-edge angle ϑ_{CE} and the functional angle of the weight-bearing area ϑ_F, both determined from the radiographs of the latest follow-up. The positive correlation is statistically significant ($R^2 = 0.93$)

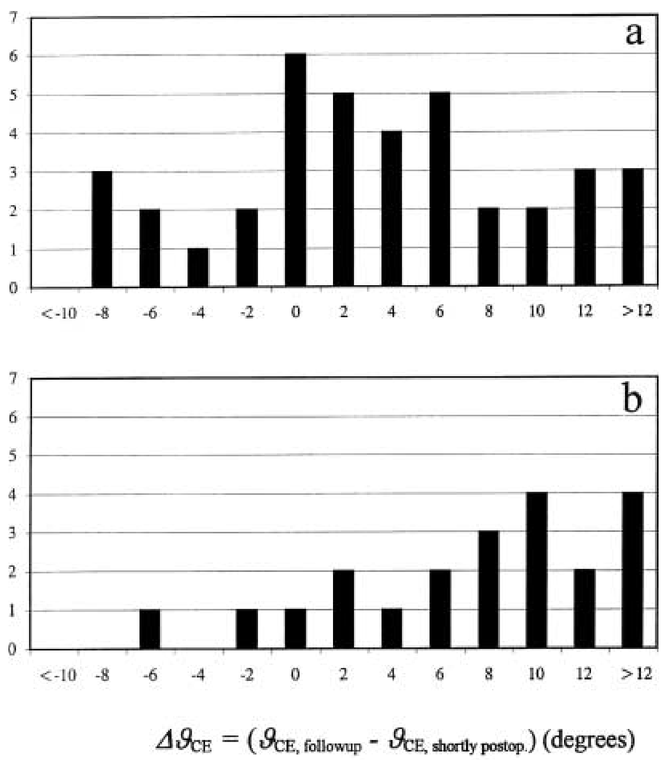

Fig. 5 a, b The histograms of the change of the centre-edge angle during the follow-up period $\Delta\vartheta_{CE}$ corresponding to the operated hips (**a**) and to the contralateral nonoperated hips (**b**). The average value for the operated hips is 3°, while the average value for the nonoperated hips is 9°. The difference is statistically significant. The probability by the pooled *t*-test *p* is less than 0.005

hand, it can be seen from the model equations [19] that the coordinate of the pole θ depends solely on the sum of the inclination of the resultant hip joint force ϑ_R and the centre-edge angle ϑ_{CE}, which are dimensionless quantities and therefore independent of the size. A better correlation obtained in the functional angle of the weight bearing area ϑ_F indicates that in samples where there are large differences in the hip and pelvis size, the parameter ϑ_F is more relevant.

Next we studied the change of the centre-edge angle during the follow-up period $\Delta\vartheta_{CE}$ ($\Delta\vartheta_{CE} = \vartheta_{CE}$ at the latest follow-up minus ϑ_{CE} shortly after the operation). If $\Delta\vartheta_{CE}$ is positive, the centre-edge angle increased, while if it is negative, the centre-edge angle decreased during this period. Figure 5 shows the histograms corresponding to the operated hips (a) and the nonoperated contralateral hips (b). The average $\Delta\vartheta_{CE}$ in the population of the operated hips is 3°, while the average $\Delta\vartheta_{CE}$ in the population of the nonoperated contralateral hips is 9°. This difference is statistically significant ($p < 0.005$). In the population of the nonoperated hips, there were only 3 (15%) in which ϑ_{CE} decreased, while in the population of the operated hips, 11 (27%) underwent a decrease in ϑ_{CE}. In the operated hips we found a weak positive correlation between the postoperative ϑ_{CE} and ϑ_{CE} at the latest follow-up ($R^2 = 0.29$) (not shown).

Figure 6 shows the correlation between the change of the centre-edge angle during the follow-up period $\Delta\vartheta_{CE}$ and the functional angle of the weight-bearing area ϑ_F determined from the radiographs of the latest follow-up. It

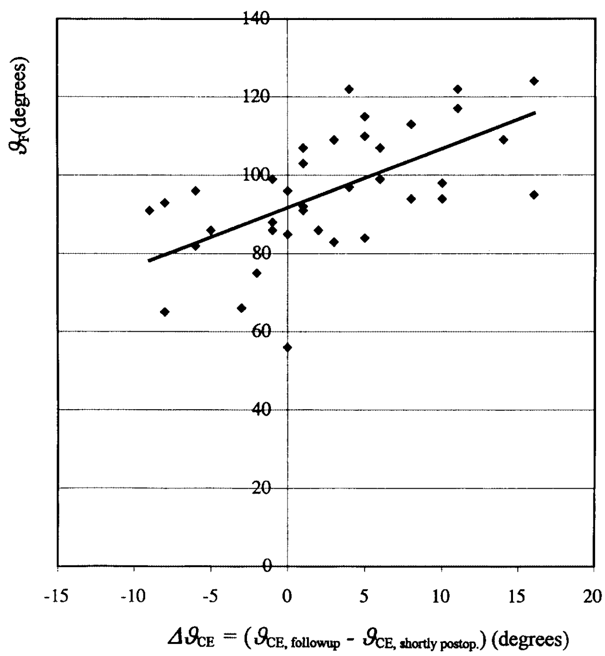

Fig. 6 The correlation between the change of the centre-edge angle during the follow-up period $\Delta\vartheta_{CE}$ and the functional angle of the weight-bearing area ϑ_F determined from the radiographs of the latest follow-up. The positive correlation is statistically significant ($R^2 = 0.37$)

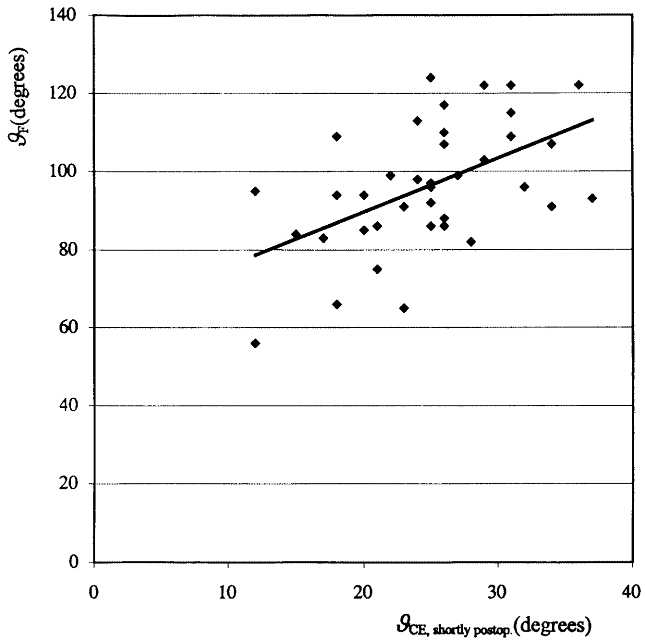

Fig. 7 Correlation between the postoperative centre-edge angle ϑ_{CE} and the functional angle of the weight-bearing area ϑ_F determined from the radiographs of the latest follow-up. The statistical significance of the negative correlation is weak ($R^2 = 0.27$)

can be seen that ϑ_F at the latest follow-up is larger if $\Delta\vartheta_{CE}$ is larger. The correlation is statistically significant ($R^2 = 0.37$).

Finally, we present the influence of the postoperative pelvis geometry on the long-term effect on the biomechanical state of the hip. Figure 7 shows the correlation between the postoperative ϑ_{CE} and the functional angle of the weight-bearing area ϑ_F determined from the radiographs of the latest follow-up. The statistical significance of the correlation is weak ($R^2 = 0.27$).

Discussion

Our results confirm that the centre-edge angle is an important parameter in determining the contact hip joint stress distribution, but other parameters (the radius of the femoral head, the width and the height of the pelvis, and the position of the greater trochanter) also affect the stress distribution (Figs. 3 and 4). For example, in two hips with almost the same centre-edge angle (≅ 20°) the peak stress normalized by the body weight was shown to differ several times (Fig. 3). Therefore, it would be relevant to study the correlation between the contact stress distribution shortly after the operation and that at the latest follow-up. Unfortunately, the mathematical model for the calculation of the resultant hip joint force used in this work does not apply to young children.

One of the reasons for the large scattering of p_{max}/W_B is that the analyzed images differ considerably in size due to the different ages of the children involved in the study. Another effect that contributes to the scattering of the results is the lack of a standard reference for the dimensions on the image, so that the exact magnification of the images of the individual patients was not known. It would be convenient if in the future while taking radiographs, a standard of known dimensions were mounted at the level of the femoral head centres – at the tip of the greater trochanter. This would contribute to lowering the noise included in the information.

We avoided the effect of the size by considering another parameter, namely the functional angle of the weight-bearing area ϑ_F (the size of the weight-bearing area divided by the square of the radius of the articular surface). By using this parameter, we avoided the effect of the image size as θ depends solely on the sum of the inclination of the resultant hip force and the centre-edge angle [19], which are dimensionless. The functional angle of the weight-bearing area is a result of the self-consistent solution of the model equations [19] that also gives the hip joint contact stress distribution. It therefore reflects physical quantities and is not solely a morphological parameter like the percentage of the coverage of the femoral head [27].

An increase of the centre-edge angle through the growth period shows the development of the bony acetabulum. We found (Fig. 5) that in the group of the operated hips, many of them underwent a decrease of the centre-edge angle during the follow-up period. In the group of the non-operated contralateral hips, there were only 3 such hips. By analysing the correlation between the change of the centre-edge angle and the functional angle of the weight-bearing area (Fig. 6), we found that a less favourable stress distribution (ϑ_F smaller) is linked to a decrease of the centre-edge angle, while a more favourable stress distribution (ϑ_F larger) is connected to an increase of the centre-edge angle, which is in agreement with expectations. One of the reasons for the differences in the development of the operated hips with respect to the contralateral nonoperated hips could be vascular derangement of the arterial supply to the acetabulum during the operation.

In order to draw conclusions regarding the optimal postoperative geometry, we studied the correlation between the postoperative centre-edge angle ϑ_{CE} and the functional angle of the weight-bearing area ϑ_F at the latest follow-up. We found that on average a larger postoperative centre-edge angle would yield a larger ϑ_F, which is biomechanically favourable. A smaller postoperative centre-edge angle would yield a smaller ϑ_F, which is biomechanically unfavourable. Although the statistical significance of this correlation is poor, comparison with the other results presented in this work indicates that a larger postoperative centre-edge angle yields on average a larger functional angle of the weight-bearing area at the long-term follow-up.

It has been suggested [33] that the reasons for degenerative changes and radiographically dysplastic hips are probably mechanical in nature and related to an increased hip joint contact stress. Mathematical modelling can give insight into the development of the hip and can therefore be of help in explaining these features and in deciding for the optimal treatment. Our results favour the hypothesis that a procedure yielding a larger weight-bearing area results in a biomechanically more favourable outcome. However, for a definitive answer, more studies including improvements to the model specific for the state of the hip after a Salter osteotomy, as well as after other osteotomies for the treatment of dysplastic hips [6, 8, 35], would be required.

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