Biomechanical analysis of the periacetabular hip osteotomy. A case report

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ABSTRACT

We determined biomechanical parameters (magnitude of the resultant hip force, its inclination with respect to the vertical, contact hip stress, position of the stress pole, size of the load bearing area, functional angle of the load bearing area and stress gradient index) in a single patient before and after the periacetabular osteotomy. The operation was performed due to hip dysplasia. We used two mathematical models to determine the resultant hip force in the one legged stance: the HIPSTRESS model (1) and the one-muscle model (2). Stress was calculated by using the HIPSTRESS model for contact stress (2). The geometrical parameters needed for calculation of biomechanical parameters were assessed from standard anteroposterior radiograms taken from the archive. Before operation, both hips were dysplastic according to the HIPSTRESS method criterion. We found considerable improvement of the contact stress distribution in the operated hip, however, contact hip stress became less favorable in the contralateral hip after the operation. After the operation, the operated hip became normal while at the contralateral side, the degree of the dysplasia has increased.

1. Introduction

The periacetabular osteotomy is supposed to reduce the disadvantageous distribution of pressure in the hip joint. It is a surgery designed to re-shape the hip joint for patients with hip dysplasia using a series of controlled breaks in the pelvic bone (3,4). Periacetabular osteotomy allows for extensive acetabular reorientation, including medial and lateral displacement of released elements (5). It was suggested that the Ganz osteotomy is indicated in patients suffering from constant pain related to the loading of the hip, provided that the range of motion allows correction without remarkable compromise of function (6). However, it requires highly skilled surgeon (7).

A study has shown that arthrosis is caused by hip dysplasia in nearly half of the treated hips (8). It is believed that hip dysplasia increases the joint contact pressures that cause degenerative changes and secondary arthrosis (9). Dysplasia of the hip is characterized by malpositioning of the proximal femur in a shallow acetabulum, providing deficient femoral head coverage (10). Early surgical treatment of hip dysplasia that preserves the joint is thought to prevent or defer the natural history of arthrosis (11).

The purpose of the periacetabular osteotomy is to improve hip and pelvis geometry as to alleviate unfavorably high contact stress in the hip joint and thereby slow down or prevent early degeneration of the hip cartilage (8,11). Namely, clinical studies have provided evidence in favor of the hypothesis that long lasting too high stress in the hip causes degeneration of the cartilage.

In order to describe the status of the hip and better understand the mechanisms of different pathologies in this region, various mathematical models were constructed. The mathematical model HIPSTRESS for calculation of the resultant hip force (1) was validated by several clinical studies (12-17) and has been proven useful in many different pathologies. HIPSTRESS model for stress (18,19) was used to study the effect of the periacetabular osteotomy (18). It was shown that hips with poor coverage of the femoral head by the acetabulum have unfavorable contact hip stress distribution (18). In these hips, stress attains its highest value at the edge of the acetabluar roof and falls off rapidly in the radial direction (18). A clinical study (20) showed that the theoretical predicitions were in agreement with the result of the biomechanical analysis.

Here we focus on a single subject. We calculated biomechanical parameters before the operation and after the operation to describe the change of the biomechanical status in a particular patient treated by periacetabular osteotomy for hip dysplasia.

2. Material and methods

We calculated biomechanical parameters (magnitude of the resultant hip force, its inclination with respect to the vertical, contact hip stress, position of the stress pole, size of the load bearing area, functional angle of the load bearing area and stress gradient index) by using two mathematical models (the acknowledged HIPSTRESS model and a simple model with one effective muscle force). Both models have previously been described in detail elsewhere (2,21,22).

Briefly, in both models for resultant hip force in the one-legged stance the body is imagined as composed of two segments: the loaded leg and the rest of the body. The equilibrium equations for forces and for torques of both segments are taken into account. The HIPSTRESS model includes nine effective muscles (gluteus minimus anterior, middle and posterior, gluteus medius anterior, middle and posterior, tenskor fasciae latae, rectus femoris and piriformis) while the simple model includes only one effective muscle.

In the model for stress, the validity of the Hook's law implies that stress is proportional to strain within the cartilage. Consequently, stress is a cosine function of the space angle between a radius vector to the chosen point and a radius vector to the stress pole (a point at the articular sphere where stress is the highest),

$$p = p_0 \cos \gamma \quad , \tag{1}$$

where p_0 is stress at the stress pole (P) and γ is the space angle. The position of the stress pole is given in the frontal plane by the inclination angle with respect to vertical (Θ) which is considered positive in the lateral direction from the vertical axis and negative in the medial direction from the vertical axis (22). The sum of the contact stresses over the contact surface is equal to the force **R**,

$$\mathbf{R} = \int p \, \mathbf{dA} \quad , \tag{2}$$

where **dA** is the area element of the load bearing area. Integration is performed over the entire load bearing area which is defined as a part of the articular sphere bounded by two planes: a plane through the center of the femoral head which is inclined for ϑ_{CE} (center-edge angle) with respect to vertical and a plane which is inclined for $\pi/2$ from the position of the pole Θ (22).

The the load bearing area is a part of an articular sphere bounded by the cuts of the sphere with two planes through the center of the sphere: one inclined as to include the most lateral point of the acetabular roof and the other defined by the condition that the cosine function reaches the value 0. The solution of the component equations for the vector of resultant hip force as an integral of stress over the load bearing area yields a system of three equations which are solved for two angle coordinates of the stress pole (polar angle Θ and azymuth angle Φ) and the value of stress at the pole p_0. If the pole lies within the weight bearing area, the value of stress at the pole is also the maximal stress that is attained on the weight bearing area p_{max}. If the pole lies outside the load bearing area, the maximal stress it attained at the point of the load bearing area that is closest to the pole. All models use as an input data geometrical parameters of pelvis and proximal femora in order to estimate the positions of the muscle attachment points, half interhip distance x_{CM}, radius of the articular sphere r and coverage of the femoral head by the acetabulum ϑ_{CE} (Figure 1).

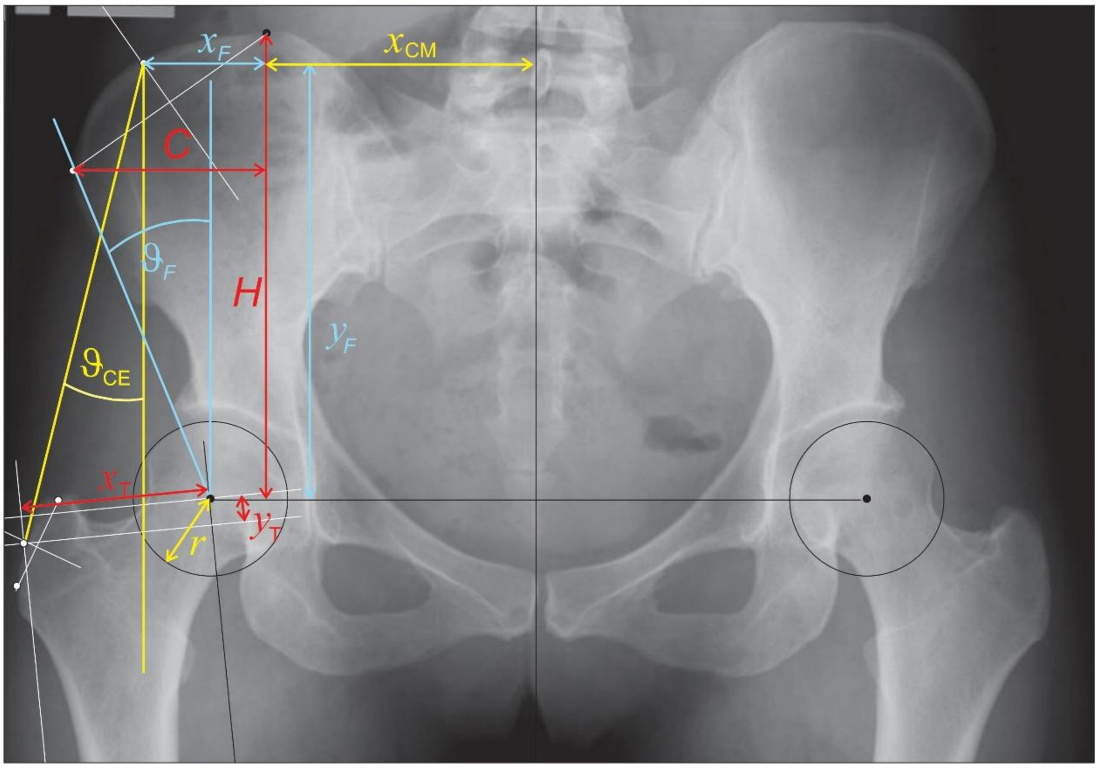

Figure 1. Geometrical parameters of the HIPSTRESS model for resultant hip force. Parameters used in the HIPSTRESS model for the resultant hip force are marked by red color, parameters used in the one-muscle model for the resultant hip force are markey by the blue color and parameters used to calculate stress are marked by yellow color.

Aside from the interhip distance, the geometrical parameters of the force models are specific to the model (Figure 1). As there were no data available on the body weight of the patient and there was also no unit length in the X ray picture, we determined dimensionless quantities: forces normalized to the body weight W_B (F/W_B and R/W_B, respectively), stresses and stress gradient index normalized with respect to the body weight and with respect to the radius of the articular sphere (p_0r^2/W_B, $p_{max}r^2/W_B$ and G_pr^3/W_B, respectively). These parameters expose the importance of hip and pelvis geometry.

X ray pictures of a patient that underwent a pelvic osteotomy were retrieved from the archive of the Department of the Orthopaedic Surgery, University Medical Centre Ljubljana, in an electronic form. The first picture was taken within a month before the surgery and the second was taken within a week after the surgery. The pictures were printed on a A4 paper and the geometrical parameters were measured manually by using a plastic ruler (estimating 5% of error).

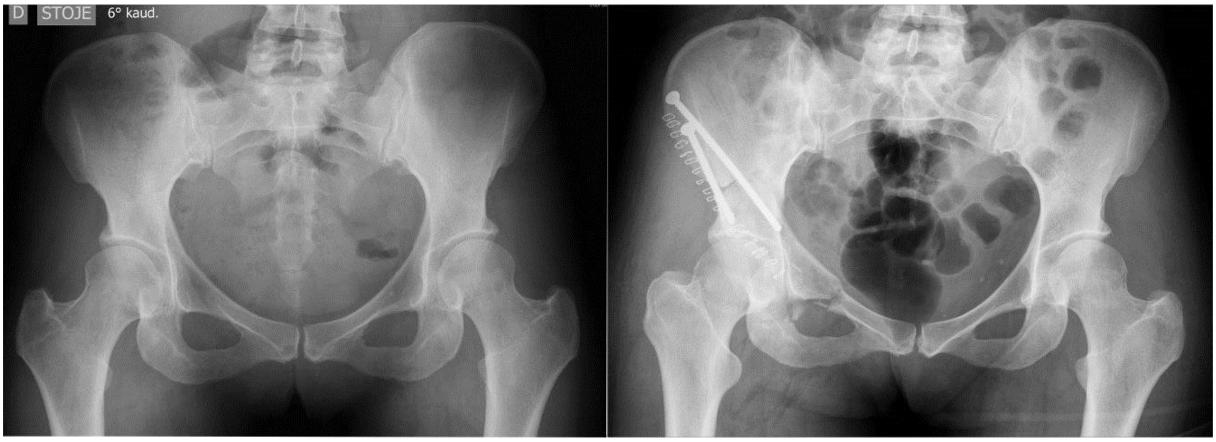

Figure 2. Standard anteroposterior radiograms of pelvis and both proximal femora of a patient that was treated by periacetabular osteotomy due to hip dysplasia. The image on the left was taken before the surgery and the image on the right was taken after the surgery.

3. Results

Scaling of the pictures (Fig. 2) was appropriate since the difference in measured femoral heads size was estimated 5% and no additional scaling was needed. We noticed a considerable (65%) increase of the centre-edge angle in the right hip after the operation (Table 1). The centre-edge angle before the operation was 12 degrees which indicates that the hip was dysplastic, while after the operation it was 27 degrees which can be considered as normal. As the increase of the centre-edge angle was intended by the surgeon it can be concluded that the operation was successful.

However, in the contralateral hip, the centre-edge angle has decreased after the operation, albeit this decrease was smaller (it decreased from 21 degrees to 15 degrees (33%)) (Table 2). Another notable change in both hips was a change of the parameter y_T (the vertical position of the greater trochanter) (Tables 1 and 2), however, change in this parameter does not crucially affect the biomechanical parameters (22).

A considerable decrease of normalized stress in the pole and of normalized peak stress on the load bearing surface took place after the operation in the operated hip (Table 3). Both models indicate more than 50% decrease in the respective parameters (Table 3). Concomitantly, the effective angle of the load bearing area has considerably increased (for more than 40%). Moreover, the sign of the stress gradient has become negative, as pertaining to normal hips (12). The biomechanical analysis clearly shows beneficial effect of the operation on the operated hip as stress is relieved and the load bearing area increased.

Table 1: Geometrical parameters of the hip that was operated, before and after the operation.

Operated hip	HIPSTRESS model			One-muscle model		
Parameter	Before operation	After operation	Difference (%)	Before operation	After operation	Difference (%)
x_{CM} (cm)	8.4	8.3	-1%	8.4	8.3	-1%
H (cm)	11.7	12.0	-3%			
C (cm)	3.7	3.5	-5%			
x_T (cm)	4.9	4.4	-10%			
y_T (cm)	0.9	0.5	-55%			
x_F (cm)				2.7	2.6	-4%
y_F (cm)				10.5	10.9	3%
r (cm)	1.9	1.8	-5%	1.9	1.8	-5%
ϑ_F (degrees)				10	8.5	-17%
ϑ_{CE} (degrees)	12	27	65%	12	27	65%

Table 2: Geometrical parameters of the contralateral hip before and after the operation.

Contralateral hip	HIPSTRESS model			One-muscle model		
Parameter	Before operation	After operation	Difference (%)	Before operation	After operation	Difference (%)
x_{CM} (cm)	8.4	8.3	-1	8.4	8.3	-1
H (cm)	12.1	12.0	-3			
C (cm)	3.1	3.7	18			
x_T (cm)	4.9	4.9	0			
y_T (cm)	1.0	1.2	18			
x_F (cm)				2.4	2.9	19
y_F (cm)				10.9	10.6	3
r (cm)	1.9	1.8	-5	1.9	1.8	-5
ϑ_F (degrees)				9	7	-25
ϑ_{CE} (degrees)	21	15	-33	21	15	-33

Table 3: Biomechanical parameters of the operated hip before and after the operation.

Operated hip	HIPSTRESS model			One-muscle model		
Parameter	Before operation	After operation	Difference (%)	Before operation	After operation	Difference (%)
F/W_B				1.6	1.7	6
ϑ_R (degrees)	9.5	7	-31	6.5	5.6	-15
R/W_B	2.7	2.8	4	2.4	2.6	8
Θ (degrees)	41.2	20	n.a.	42.8	22	n.a.
p_0r^2/W_B	4.12	1.93	-73	3.77	1.77	-72
$p_{max}r^2/W_B$	3.59	1.93	-55	3.56	1.77	-69
ϑ_f (degrees)	60.8	97	45	59.2	95	46
G_pr^3/W_B	2.013	-0.24	n.a.	1.93	-0.15	n.a.

Table 4: Biomechanical parameters of the contralateral hip before and after the operation.

Contralateral hip	HIPSTRESS model			One-muscle model		
Parameter	Before operation	After operation	Difference (%)	Before operation	After operation	Difference (%)
F/W_B				1.77	1.71	-3
ϑ_R (degrees)	10.0	9.0	-11.0	6.0	4.6	-26
R/W_B	2.7	2.6	-4	2.6	2.56	-2
Θ (degrees)	25.5	33.0	n.a.	33.2	33	n.a.
p_0r^2/W_B	2.40	2.96	21	2.4	2.6	8
$p_{max}r^2/W_B$	2.39	2.81	15	2.35	2.47	5
ϑ_f (degrees)	85.5	72	-15	78	72	-8
G_pr^3/W_B	0.19	0.92	n.a.	0.50	0.80	n.a.

In the contralateral hip, the increase of the centre edge angle caused an increase of the stress in the pole and on the load bearing area and concomittant decrease of the load bearing area (Table 4), however, to a smaller extent (not larger than about 20%).

Discussion

The biomechanical analysis has shown that after the operation, stress distribution has considerably improved in the operated hip, however, it has become less favorable in the contralateral hip. As the parameter that is the most important in dysplastic hips is the centre edge angle, an error in determination of the centre edge angle could partly contribute to the outcome of the analysis. Positioning the image (determining horizontal and vertical axes) is crucial in determination of the geometrical parameters.

Performing the analysis with two models has shown that their predictions were qualitatively equivalent. An advantage of the one-muscle model in the form as used in this work is that it is independent of the size of the picture. As we did not have an unit length present in the pictures it was favorable for us to use the model which in not burdened with the size effect. The HIPSTRESS model for the resultant hip force however, includes reference coordinates of the muscle attachment points in 3 dimensions. Therefore, in the cases when the actual sizes are not known, this may present a bias.

The periacetabular osteotomy is used in dysplastic hips to increase the load-bearing area of the hip and to prevent osteoarthritis (11). Many articles showed that the periacetabular osteotomy is very successful to prevent arthrosis. But some of them indicate considerable arthrosis progression after the surgery in the operated hip (9, 20). Our results however indicate that the contralateral hip should also be monitored as the surgery affects both hips.

Conclusions

Our findings indicate that determination of biomechanical parameters is valuable for monitoring the stress distribution and the load-bearing area in the hip joint of patients before and after periacetabular osteotomy because it may show us the disguised malformations of both hips hip before they could be detected by deformations on X ray images. We will research more on the matter in our future work.

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