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ORIGINAL ARTICLE

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Influence of contact hip stress on the outcome of surgical treatment of hips affected by avascular necrosis

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Abstract *Introduction:* Biomechanical analysis is an important tool that could improve the treatment of a diseased hip. However, it is still unclear how the biomechanical status affects the clinical outcome of a certain disease. In this work we studied the long-term effect of contact hip stress on the clinical outcome of hips that were operated on by various intertrochanteric osteotomies due to avascular necrosis of the femoral head. The hypothesis being tested is that the hips with a more favourable postoperative distribution of contact hip stress have a better clinical outcome. *Materials and methods:* The study was performed on a population of 30 hips. For each hip, we determined the peak contact hip stress before the operation and immediately after the operation by using a recently developed method based on a three-dimensional mathematical model and the data from standard anteroposterior roentgenographs of both hips and pelvis. The hips were evaluated clinically 9–26 years after the operation and divided into a successful and an unsuccessful group. The average change of the peak stress due to the operation was calculated for each group, and the values were compared by *t*-test. *Results:* In the successful group the operation caused an average decrease of the peak hip stress of about 10%, while in the unsuccessful group the operation caused an average increase of the peak hip stress of about 4%, the difference between the respective changes of the peak stress due to the operation being statistically significant (p=0.001). *Conclusion:* Our results support the hypothesis that the hips with a more favourable postoperative distribution of contact hip stress have a better clinical outcome.

Keywords Femur head necrosis · Biomechanical analysis · Contact hip stress · Avascular necrosis

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Introduction

The treatment of avascular necrosis of the femoral head presents a great challenge in orthopaedic surgery. Although it has been studied extensively, the aetiology and pathogenesis of the disease are incompletely understood, and we still do not know the best method of treatment. So, new information that may be acquired through additional research and careful analysis would be helpful.

The distribution of contact stress in the hip is an important factor which affects the development of the hip and also determines the state of health or disease of the adult hip [3, 19]. A number of clinical conditions may alter the contact stress in the hip joint, most often by reducing the contact area (dysplasia, improperly reduced acetabular fractures), but also by creating non-congruent surfaces (Perthes disease) [3]. Elevated hip joint contact stress is regarded as an unfavourable biomechanical state of the hip and is assumed to be a cause of arthrosis.

Avascular necrosis of the femoral head is characterised by variable areas of dead trabecular bone and bone marrow, extending to the subchondral plate. The affected part of the femoral head progressively deteriorates. Eventually, a part of the surface of the femoral head can no longer bear weight. As the load is then distributed over a smaller weight-bearing area, the stress distribution is also affected, increasing the stress. The condition usually leads to the early development of secondary osteoarthrosis [18].

In order to treat avascular necrosis of the femoral head, different osteotomies involving the proximal femur were introduced. The main goal of these operations is to remove the damaged area of the femoral head surface from the region of high contact stress and to replace it with the sound area. The elevated stress would thereby be diminished. It was indicated [7] that an increased contact hip stress results from an excessive resultant hip joint force, from too vertical a direction of a resultant hip joint force and from an insufficient weight-bearing area [additionally determined by the extent of the coverage of the femoral head (Wiberg angle ϑ_{CE}) and from the size (radius) of the femoral head].

The aim of this study was to estimate the influence of contact hip stress on the long-term clinical outcome of the surgical treatment of hips subject to avascular necrosis of the femoral head. The results are expected to help with clinical work dealing with avascular necrosis of the femoral head and with the selection of a specific intertrochanteric osteotomy to achieve the optimal postoperative hip geometry.

Patients and methods

We considered 30 hips (27 patients) which were surgically treated between 1972 and 1991 at the Department of Orthopaedic Surgery in Ljubljana. The operations were performed by four different surgeons. The group of patients comprised 22 men and 5 women, average age 39 years (range 25–55 years). The patients were followed for 9–26 years on a yearly basis. The hips considered in this work were subjected to different intertrochanteric osteotomies (Fig. 1). The angles of correction for flexion ranged from 20° to 30° and for varisation or valgisation from 15° to 20°.

In the clinical evaluation, the hips were divided into two groups: the group with successful clinical results (excellent or good results) and the group with unsuccessful clinical results (fair or poor results). The following criteria were used to evaluate the clinical success of the operation [20]:

- Excellent results: no radiological progression of necrosis for 9–26 years postoperatively, and no signs of osteoarthritis.
- Good results: no progression of the disease for 8 years postoperatively; followed later by slow, radiologically documented progression of necrosis associated with discomfort after walking long distances.
- Fair results: collapse of the femoral head occurring 3–8 years postoperatively.
- Poor results: collapse of the femoral head occurring within 3 years postoperatively, requiring total hip replacement.

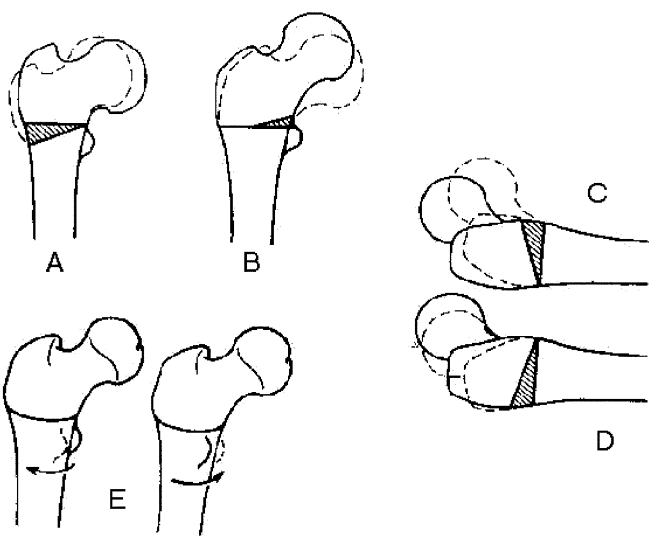

Fig. 1 Various types of intertrochanteric osteotomies: valgisation (*A*), varisation (*B*), flexion (*C*), extension (*D*), rotation (*E*)

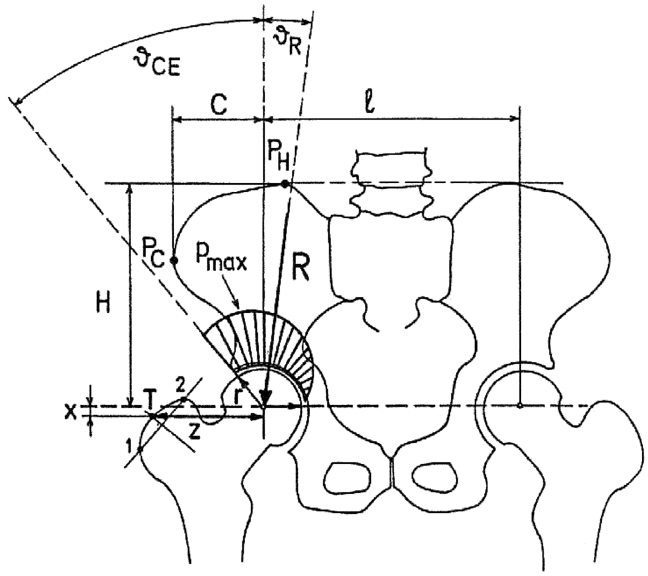

Fig. 2 The geometrical parameters of the hip and pelvis needed for determination of the peak stress on the weight-bearing area. The stress distribution and the resultant hip joint force $\boldsymbol{R}$ are also shown schematically. Symbol ϑ_R denotes the inclination of $\boldsymbol{R}$ with respect to the vertical, and the point T denotes the effective muscle attachment point on the greater trochanter

The contact stress distribution in the hip joint was determined by the HIPSTRESS computer program [11]. This program consists of two procedures: one for the determination of the hip joint contact stress distribution and the other for the determination of the resultant hip joint force $\boldsymbol{R}$. The procedure for the determination of the hip joint contact stress distribution is based on a mathematical model [13, 14] and requires as input data the magnitude and the direction of the resultant hip joint force $\boldsymbol{R}$, the radius of the hip joint articular surface (r) and the centre-edge angle of Wiberg (ϑ_{CE}) (Fig. 2). The procedure for the determination of the resultant hip joint force $\boldsymbol{R}$ is based on a three-dimensional mathematical model of the hip joint in the one-legged stance [12, 17]. This program requires as input the distance between the two femoral head centres (l), the coordinates of the effective muscle attachment point on the greater trochanter with respect to the femoral head centre (point T), the height of the pelvis (H), the horizontal distance between the most lateral point on the iliac crest and the femoral head centre (C) (Fig. 2) and the body weight (W_B). The body weight of the patients was measured immediately before the operation. The geometrical parameters were determined from the standard anteroposterior (AP) radiographs using the computer HIJOMO program [15]. We digitized the profiles of both proximal femurs and acetabula, and some characteristic points as described in detail elsewhere [15, 23]. An average magnification of 10% was taken into account. The reference values of the model muscle attachment points [9] were rescaled in order to adjust the configuration of the hip and pelvis of the individual patient. We assessed hip stress before and immediately after the operation.

The stress distribution is presented by the maximal value of stress on the weight-bearing area (p_{max}) and also by the peak stress calculated with respect to the body weight (p_{max}/W_B) which gives the effect of hip geometry. Low p_{max} and p_{max}/W_B are biomechanically favourable, while high p_{max} and p_{max}/W_B are biomechanically unfavourable. The average values of the resultant hip force were also calculated with respect to the body weight (R/W_B) because the normalized quantities emphasise the effect of hip geometry. We also present some additional biomechanical parameters such as the inclination of the resultant hip force (ϑ_R) and the position of the stress pole (Θ).

The model of hip stress [13, 14] assumes that a hemispherical portion of the femoral head is able to bear load. Therefore, it is strictly valid only for hips in which no part of the weight-bearing area has collapsed. In order to approximate the preoperative state, we assessed stress in the early stages of avascular necrosis when the femoral heads were still relatively sound and able to carry their load. To approximate the postoperative state, we assumed that the collapsed area had been moved away from the weight-bearing region.

The person who evaluated the clinical outcome and the person who determined the hip stress were blinded with respect to each other. The person who evaluated the clinical outcome did not perform any of the operations analysed.

The data were analysed by descriptive statistical methods and expressed by average values and t-test probability.

Results

First we analysed the preoperative values of the peak contact stress (p_{max}) in both groups (successful/unsuccessful clinical results) of patients; the null hypothesis was that the two groups are equal with respect to p_{max}. We found no statistically significant differences in p_{max} (p=0.63) (Table 1). The average values of the peak stress (p_{max}) in both groups lie within the range of values corresponding to normal hips [3].

Next we studied the effect of the change of the peak stress due to the operation ($\Delta p_{max} = p_{max\ post\ op} - p_{max\ pre\ op}$) on the clinical outcome; the null hypothesis was that the two groups are equal with respect to Δp_{max}. It was found that Δp_{max}had an important influence on the final clinical outcome (Table 2, Fig. 3). In the successful group, the peak contact stress decreased on average by 10%, while in the unsuccessful group it increased by about 4%.

In both groups of patients, we analysed various biomechanical parameters preoperatively and postoperatively (Tables 3 and 4); the null hypotheses were that the two groups are equal with respect to the corresponding parameter. In the successful group of patients, all of the parameters showed a biomechanically favourable tendency: the average values of stress on the weight-bearing area (p_{max}) and the peak stress calculated with respect to body weight (p_{max}/W_B) had decreased by 10%, the average values of the resultant hip force calculated with respect to body weight (R/W_B) had decreased by approximately 7%, the average inclination of the resultant hip force (ϑ_R) had increased by 17%, while there was a decrease of the stress pole position (Θ) of around 15%. In the unsuccessful group of patients, however, all analysed parameters showed a biomechanically unfavourable tendency (Table 4).

We also analysed the effect of different intertrochanteric osteotomies on the change of the peak contact stress. The list of operated hips, the type of osteotomy, the change of peak hip stress and final clinical outcome are given in Table 5. In 7 hips which underwent flexion-varisation intertrochanteric osteotomy, the average peak contact stress had decreased by 380 kPa on average, while in 10 hips with flexion osteotomy, it had decreased by 150 kPa on average. In 6 patients with valgisation-flexion osteotomy,

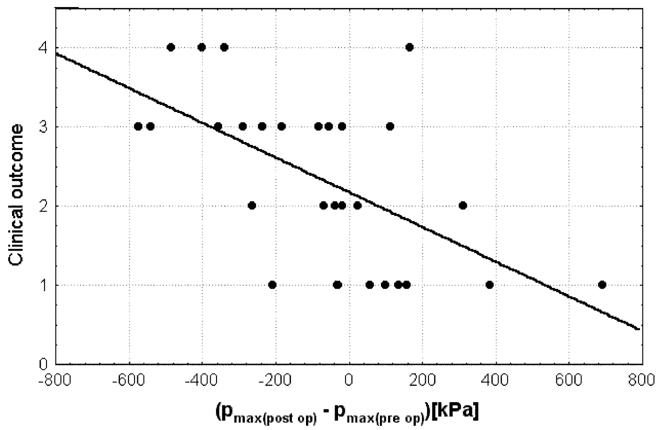

Fig. 3 Clinical outcome as a function of Δp_{max}: 4 (excellent), 3 (good), 2 (fair), 1 (poor). The *solid line* represents the best fit by the linear function

Table 1 Preoperative peak stress (p_{max}) in the clinically successful and unsuccessful groups and the probability indicating the statistical significance of the difference between the respective values

	Successful	Unsuccessful	p (t-test)
p_{max}(kPa)	2107±345	2208±719	0.63

Table 2 Change of peak stress due to operation in the clinically successful and unsuccessful groups and the probability indicating the statistical significance of the difference between the respective values

	Successful	Unsuccessful	p (t-test)
Δp_{max}(kPa)	–220	80	0.0017

Table 3 Average values of various biomechanical parameters preoperatively and postoperatively in the successful intertrochanteric group of patients and the corresponding probabilities describing the statistical significance of the differences

	Preoperatively	Postoperatively	Δ (%)	p (t-test)
P_{max} (kPa)	2107±345	1887±283	–10	0.067
P_{max}/W_b(m^{-2})	2917±769	2602±637	–11	0.231
R/W_b	2.668±0.17	2.490±0.17	–7	0.008
ϑ_R (°)	7.22±1	8.42±1.56	17	0.018
Θ (°)	20.76±5.55	17.56±5.11	–15	0.112

Table 4 Average values of various biomechanical parameters preoperatively and postoperatively in the unsuccessful intertrochanteric group of patients and the corresponding probabilities describing the statistical significance of the differences

	Preoperatively	Postoperatively	Δ (%)	p (t-test)
P_{max} (kPa)	2208±719	2289±858	4	0.784
P_{max}/W_b(m^{-2})	2780±1066	2886±1226	4	0.803
R/W_b	2.539±0.12	2.593±0.22	2	0.405
ϑ_R (°)	7.56±0.93	7.35±1.76	–3	0.682
Θ (°)	20.73±9.25	21.15±9.91	2	0.905

Table 5 List of operated hips, ype of osteotomy, change of peak hip stress and final clinical outcome

Case	Type of osteotomy	Δp_{max} (kPa)	Clinical outcome
1	Flex.var.ost	–575.1	Good
2	Flex.var.ost	–541.0	Good
3	Flex.var.ost.	–484.2	Excellent
4	Flex.var.ost.	–401.1	Excellent
5	Flex.ost.	–354.7	Good
6	Flex.var.ost.	–338.3	Excellent
7	Flex.ost.	–288.5	Good
8	Flex.ost.	–263.0	Fair
9	Flex.var.ost.	–237.8	Good
10	Flex.ost.	–208.5	Poor
11	Flex.ost.	–182.5	Good
12	Flex.var.ost	–80.5	Good
13	Flex.ost.	–68.3	Fair
14	Flex.ost.	–54.8	Good
15	Flex.ost.	–37.6	Fair
16	Flex.ost.	–33.1	Poor
17	Flex.ost.	–29.4	Poor
18	Valg.flex. ost.	–18.8	Good
19	Min.flex.ost.	–16.9	Good
20	Min.flex.ost.	–16.8	Fair
21	Min.flex.ost.	24.1	Fair
22	Valg.min.flex.ost.	56.3	Poor
23	Valg flex.ost.	98.6	Poor
24	Valg.flex.ost.	111.5	Good
25	Valg.flex.ost.	135.5	Poor
26	Valg.flex.ost.	158.1	Poor
27	Valg.ost.	167.1	Excellent
28	Valg.ost.	311.8	Fair
29	Valg.ost.	384.5	Poor
30	Valg.ost.	690.4	Poor

the average peak contact stress had increased by approximately 90 kPa, while in 4 valgisation intertrochanteric osteotomies it had increased by approximately 390 kPa. In 3 hips which underwent flexion intertrochanteric osteotomy, the extent of flexion turned out to be smaller than planned (minimal flexion), and the postoperative peak contact stress remained practically unchanged.

Discussion

Despite extensive studies of avascular necrosis of the femoral head, its pathogenesis and optimal treatment still need to be identified. A number of attempts to preserve the femoral head for as long as possible have been reported [18], and intertrochanteric osteotomy is regarded as a relatively effective salvage procedure for hips in advanced stages. But according to the literature, the type of osteotomy that should be performed is still controversial. Several authors advocate a varus osteotomy, others recommend flexion, valgisation or a combined osteotomy [18]. Also, biomechanical studies have been made [2, 4, 5, 6, 22] based on the finite element method where the conditions pertaining to the particular stage of the disease were simulated, and the effects of different surgical methods of treatment on stresses acting in the hip and pelvis were analysed. These studies were exclusively theoretical and not linked to the clinical results. To our knowledge, this is the first study in which the biomechanical parameters of hip joint affected by avascular necrosis were evaluated in concrete clinical cases. According to our data the good correlation between the biomechanical parameters and a successful clinical outcome (Fig. 3, Tables 3 and 4) suggests the importance of the biomechanical status on the final outcome of the treatment.

The parameter Δp_{max} was found to be the most important biomechanical parameter influencing the final clinical outcome (Table 2, Fig. 3). Our results indicate that better clinical results might be expected when the operation significantly decreases the peak stress on the weight-bearing area. We believe that it is important to achieve an optimal postoperative geometry of the hip, yielding as low hip stress as possible and thereby decelerating the development of degenerative processes in the hip. Our results therefore suggest that flexion and varisation intertrochanteric osteotomies, particularly a combination of the two, are favourable procedures, while valgisation intertrochanteric osteotomy seems to be an unfavourable one. However, we would like to mention the case of a patient who showed an excellent clinical result in spite of a relatively significant increase in contact stress distribution on the weight-bearing area. We may consider this patient as a specific case within our population. Namely in this case, avascular necrosis developed during pregnancy, so the biological factor influenced the development of avascular necrosis only temporarily. Such cases are also [18] regarded in the literature as therapeutically favourable.

It was recently reported that a set of programs was developed for the simulation of various intertrochanteric osteotomies [21] that yield stress within the femoral head cartilage. Calculation of stress is based on the finite element method where the mesh corresponding to the proximal femur is constructed directly from the data obtained from CT. The method can be applied to an individual patient. The paper reports the results for a single person, while the authors plan a further study to answer the question of whether patient-specific modelling is needed or not. The advantage of the finite element method is that it gives a detailed description of stresses within the hip joint (not only the contact hip stress as in our model). Furthermore, using CT provides more data that are specific for a certain patient. As our model is three-dimensional, such additional data could also be implemented to yield a more detailed description. However, CT requires additionally exposing the patient to X-rays, which is unfavourable. Also, the input parameters for the calculation of stress are the resultant hip force in the one-legged stance and some additional geometrical parameters, which are estimated from anteroposterior roentgenographs and a suitable mathematical model. As the determination of the resultant hip force by such a method is subject to many assumptions and represents a weak link within the method, it is our opinion that the proposed method [21] with the detailed description of the proximal femur by the finite element method in combination with CT at this point of the development of models of force does not substantially perform better than our method based on Hooke's law and only a single anteroposterior roentgenograph. At this point in the development of the method, it is of interest to perform retrospective studies of large groups of patients by using the existing roentgenographs from the archives. Usually, there is a standard anteroposterior roentgenograph available and sometimes also an axial roentgenograph of the affected hip. Our method is useful in such cases [17, 23]. However, refinements of the method can be expected to prove useful in the future development of hip stress determination.

We have assumed that immediately after the operation the collapsed area of the femoral head surface was removed from the weight-bearing area. In actual fact, from the X-ray pictures we could not verify that our assumption was justified. As the collapsed region cannot bear weight in such hips, the weight-bearing area is diminished, and therefore stress is elevated. However, this could not be taken into account in our analysis.

The mathematical model for the determination of hip stress used in this work is not suitable to assess hip stress if the collapse of the femoral head has already occurred and therefore a part of the femoral head that previously bore weight can no longer perform this task. However, the model could be upgraded by taking into account that there is an area within the femoral head surface area that does not bear weight [8]. Hip stress could then be calculated if the size and the position of the defect were known. The required data could be obtained from additional roentgenographs available in the archives (usually the axial roentgenograph) or from a MR tomograph image. We are planning to develop such a model in the future and hope that it will prove useful in planning the treatment of individual patients.

To conclude, our results show that reduction of contact hip stress yields a more favourable outcome both biomechanically and clinically.

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