Stress Analysis of the Hip Bone

Dr. Akram Abood Jaffar*   **Dr. Sadiq Jaffar Abass ****
Huma Mohamed Abdullah*

* Human Anatomy Dept. / College of Medicine / University of Al-Nahrain
** Medical Engineering Dept. / College of Engineering / University of Al-Nahrain

Abstract

The bony pelvis has a major role in weight transmission to the lower limbs. The complexities of its geometric form, material properties, and loading conditions render it an open subject to biomechanical analysis.

The present study deals with area measurement, and three-dimensional finite element analysis of the hip bone to investigate magnitudes, load direction, and stress distribution under physiological loading conditions.

The surface areas of the auricular surface, lunate surface, and symphysis pubis were measured in (35) adult hip bones. A solid model was translated into ANSYS parametric design language to be analyzed by finite element analysis method under different loading conditions.

The surface areas of the auricular surface, symphysis pubis, and lunate surface were (14.39±2.05cm², 4.46±1.01cm², and 24.63±3.2cm²) respectively. A significant positive linear relationship was found between the auricular surface area and that of the lunate surface. No such correlation was found between the auricular surface and symphysis pubis. The finite element analysis model showed that stresses, using the Von Mises method, were distributed mainly in the acetabulum (anterior, superior and posterior part: 11.2%, 5.4%, 15.9% respectively), auricular surface 24.6%, and ischial tuberosity 40.3%, when a 70kg load was applied. Stresses calculated for higher loads showed a positive direct proportional increase. Principle stresses indicated that failure occurred in the anterior and posterior surface of the acetabulum as well as in the sacrioiliac joint.

Keyword: Hip Bone, Finite Element Analysis, Stress.

Introduction:

In the musculoskeletal system, some diseases are due to mechanical or are influenced in a positive or negative sense by mechanical factors. In every case, the balance between stressing and biological reaction of the tissues of the locomotor system plays a decisive role. A careful biomechanical analysis is therefore recommended at the beginning of any prognostical or therapeutical consideration[i,ii]. Fracture risk is directly related to the ratio of tissue stress to tissue strength, which in turn is dependent on not only tissue composition but also tissue geometry and the direction and magnitude of loading. These three elements determine how the load is distributed within the tissue[iii] The bony pelvis may be considered as two arches divided by a transacetabular plane (Fig.1). The

posterior arch, chiefly concerned in transmitting weight, consists of the upper three sacral vertebrae and strong pillars of bone from the sacroiliac joints to the acetabular fossae. The anterior arch, formed by the pubic bones and their superior rami, connects these lateral pillars as a tie-beam preventing separation; it also acts as a compression strut against medial femoral thrust[iv,v].

When the weight of the body is being borne on both legs, the center of gravity is centered between the two hips and its force is exerted equally on both hips. Under these loading conditions, the weight is supported equally on the femoral heads. In symmetrical standing on both lower extremities, the compressive forces acting on each femoral head represent approximately one-third of body weight[vi,vii]. In normal walking, the hip joint is subjected to wide swings of compressive loading from one-third of body weight in the double support phase of gait to four times body weight during the single leg support phase.

Many more detailed analyses of the biomechanics of the hip have been directed toward the stresses within the femoral stem than within the acetabulum[viii,ix,x]. The intact acetabulum is a horseshoe form that wraps around the superior, anterior, and posterior aspects of the slightly eccentric femoral head. The stress is transferred from the femoral head to the acetabulum through the anterior and posterior extensions of the horseshoe[xi,xii].

Finite Element Analysis (FEA) is a computer-based numerical technique for calculating the strength and behaviour of structures, in which a structure is broken down into many small simple blocks or elements. The behaviour of an individual element can be described with a set of equations. Just as the set of elements would be joined together to build the whole structure, the equations describing the behaviours of the individual elements are joined into an extremely large set of equations that describe the behaviour of the whole structure. The computer can solve this large set of simultaneous equations. From the solution, the computer extracts the behaviour of the individual elements. From this, it can get the stress and deflection of all the parts of the structure. The stresses will be compared to allow values of stress for the materials to be used, to see if the structures are strong enough[xiii]. The use of FEA in biomechanical research has been established[xiv,xv,xvi,xvii].

The present study deals with 3-D finite element analyses of the pelvic bone, which are used to investigate its basic load transfer and stress distributions under physiological loading condition

Methods:

Thirty-five adult hip bones of Caucasoid origin were used. In each of them the surface areas of the auricular surface, lunate surface, and symphysis pubis were measured by a sheet of dental molding wax ('Tenasyle'. Associated dental products Ltd, Swindon, Uk). When an accessory sacroiliac joint was observed the area of its articular surface was added to that of the auricular surface.

Each sheet was warmed gently until pliable on a thermostatically controlled electric hot plate. The sheet was then molded carefully to the contours of

each of the articular surfaces above. The wax was trimmed exactly on the articular margin (Fig.2). The trimmed piece was then removed from the bone and weighed along with a reference piece of wax sheet of known area (900mm²=928mg). The area of the molded wax was calculated from these values[xviii].

One hip bone specimen was cross-sectioned to create a solid model constructed using 3D studio max5. The model obtained in this way reflects accurately the actual geometry of the hip bone. The 3D studio max5 program translated the data into ANSYS Parametric Design Language (APDL) of ANSYS 5.4 (ANSYS Inc.) finite element method program (Fig.3).

The model was meshed by using brick element with 8 nodes. The pelvis has been found to contain approximately 10% cortical bone and 90% cancellous bone[xix,xx]; from these percentages, a combined material property was assigned to the finite element model.

The loading conditions in the hip joint are a complex problem. Apart from the weight of the upper body, the muscles and ligaments forces operate onto the pelvis bone. For the sake of convention, the auricular surface was considered to be as an input area due to its role in load transmitting from the sacrum to the hip bone, and the lunate hip as an output area in which the forces will pass from the hip to the femur[10].

Results:

Measurements of articular surfaces:

An accessory sacroiliac joint was observed in 5% of the specimens (Fig.4), whenever it was found its surface area was added to the auricular surface. Table-1 shows the descriptive statistics of the articular areas of the hip bone. Note that the mean area of the lunate surface was 10.24cm² more than the auricular area.

The coefficient of variation for the articular surface areas was found to be 13%, 25%, 14% for the lunate, symphysis pubis and auricular surface respectively. (Fig.5) shows the frequency distributions of the areas of the lunate and auricular surfaces.

Regression analysis of the areas of the auricular surface and the lunate surface showed a significant positive linear relationship (Fig.6) with a correlation coefficient (r=0.56; p<0.0008). There was no correlation between auricular surface and symphysis pubis areas.

Model analysis by ANSYS:

Table-2 shows the summary of the calculated Von Mises stresses of the hip bone. On the lateral surface, the largest values of stresses for 70kg person were distributed in the anterior and posterior limbs of the acetabulum (11.2%, 15.9%) respectively (Fig.7). By increasing the load, it was noticed that stresses will be distributed in the superior part of the acetabulum of a value (5.4%) (Fig.8). The iliac crest, ramus of the ischium, body of the pubis, and inferior surface of the acetabulum had lower stresses compared with the previous regions.

On the medial surface, the stress was (24.6%) in the auricular surface, (40.3%) in the ischial tuberosity, and (1.5%) in the ischial spine. By increasing loads these values increased. The iliac fossa, iliac crest, and body of the ischium have lower stress values.

Discussion:

The compressive force of the body weight that passes from the sacrum to the sacroiliac joint can be resolved into two components: one will go downward and laterally to the acetabulum, while the other component goes downward and medially to the symphysis pubis. The area of the articular surface relates to its ability to resist longitudinal compression forces provided its internal structure remains constant[xxi]. Based on the above mechanical considerations, the transmission of compressive forces can be analyzed.

Our statistical analysis of the surface areas of the articulating surfaces emphasizes the fact that both the lunate and auricular surfaces are involved in force transmission through the hip bone while the symphysis pubis is merely a part of the anterior butressing arch of the articulating pelvis being involved in stability and protection. As far as the measurements of the surface areas of the articulating surfaces, this was indicated in the following:

- The significant linear relationship between the areas of the auricular surface versus that of the lunate surface. No such relation was found between the auricular and symphysis pubis articular surfaces.

- The coefficient of variation of the lunate and auricular surfaces were comparable (13% & 14%); whereas the coefficient was 25% for the symphysis pubis articular surface. Since we cannot conclude anything by simple comparing the measures of absolute dispersion, the coefficient of variation (which is simply the standard deviation of a distribution expressed as a

percentage of the mean) is the measure of the degree of relative dispersion that exists in the distributions. Thus the distributions of the areas of the lunate and auricular surfaces are comparable on the contrary to that of the area of the symphysis pubis. This supports the idea that the lunate and auricular surfaces are being related in performing a joint task; that is of weight transmission.

If we consider that, the mean surface area of the acetabulum ($29.09cm^2$) represents 100% of the load passing out of the hip bone then 49% is received through the sacroiliac joint ($14.35cm^2$). This difference indicates that magnitude of the load passing out from the acetabulum is more than that received at the sacroiliac joint. The possible reason for this is that some of the loads are applied to the acetabulum through other sources, mainly the ligaments. According to this, the ligaments play a very important role in weight transmission. Ligaments act as strong mechanical beams and they are effective only when the ligaments are inclined toward the vertical direction; therefore, because the sacrospinous ligament is nearly horizontal it will not have that effect in carrying loads. Thus, the most important ligament is the sacrotuberous ligament, which extends from ala of the sacrum downwards to the ischial tuberosity. The posterior sacroiliac ligaments are extremely thick and strong but contribute directly to sacroiliac joint stability. Vertical loading (eg. weight bearing) produces a downward motion plus rotation. During normal standing, the upper body weight on the anterosuperior aspect of the sacrum

produces an anterior sacral tilt[xxii], which causes it to sink forward and downward. This potential motion puts the posterior sacroiliac ligaments (in addition to the sacrotuberous and sacrospinous) on stretch, which is an automatic locking device[xxii, xxiii].

In the following discussion of the finite element analysis model, we will refer to the values obtained in assuming a 70kg person. The high stress found in the ischial tuberosity emphasizes the role of the sacrotuberous ligament in weight transmission as has been suggested above. The minor role on the sacrospinous ligament is indicated by the low stress values; these values are attributed to its role in stability rather than weight transmission.

Regions of the hip bone that do not lie in the line of weight transmission showed lower stress values; this is clear at the iliac crest, iliac fossa, body and ramus of the ischium.

The intact acetabulum is a horseshoe form that wraps around the superior, anterior, and posterior aspects of the slightly eccentric femoral head. In the lightly loaded state for the 70 kg, the dome of the acetabulum is relatively unloaded, and the stress is transferred from the femoral head to the acetabulum through the anterior and posterior extensions of the horseshoe as indicated in (fig 7), and it is represented by the red color (arrows). As the load is progressively applied, for the 90kg and the 110kg since the acetabulum is not in continuity inferiorly, the stresses will be distributed superiorly and the anterior and posterior sides of the horseshoe are free to expand so that a more congruous seating of the femoral head is allowed. This phenomenon of deformation under load leads to increasing congruity with progressive loading.

TABLE-1: descriptive statistics of the area (cm^2) of the articulating surfaces of the hip bone

	Lunate surface	Symphysis pubis	Auricular surface
Mean	24.63	44.58	14.39
Standard Error	0.541	0.185	0.347
Median	24.46	43.7.4	14.43
Mode	24.46	43.74	-----
Minimum	17.62	20.17	10.71
Maximum	30.26	73.6	18.74
Sample size	35	35	35

TABLE 2: **Percentages of the distribution of Von Mises stress for 70 kg body weight**

Region		Von Mises Stress Percentages For (70KG)
Sacroiliac joint		24.6%
Sacrospinous ligament		1.5%
Sacrotuberous ligament		40.3%
acetabulum	Anterior	11.2%
	Posterior	15.9%
	Superior	5.4%
Symphysis pubis		0.89%
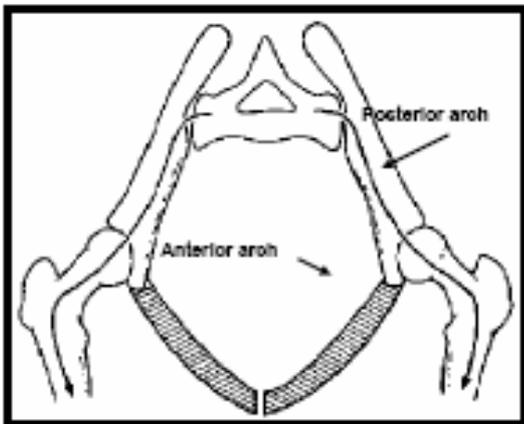
Fig.1 Digrammaic representation of hip bone mechanics
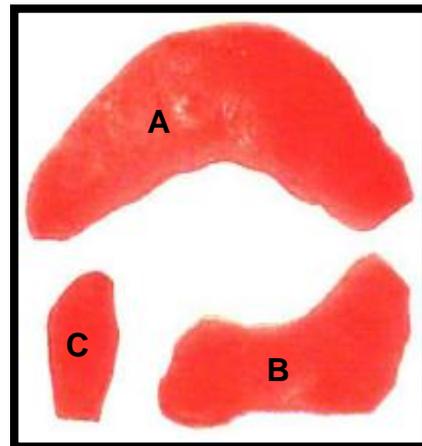
Fig.2 Example of wax pieces that fitted the articular surface of the (A) acetabulum, (B) auricular surface, & (C) symphysis pubis
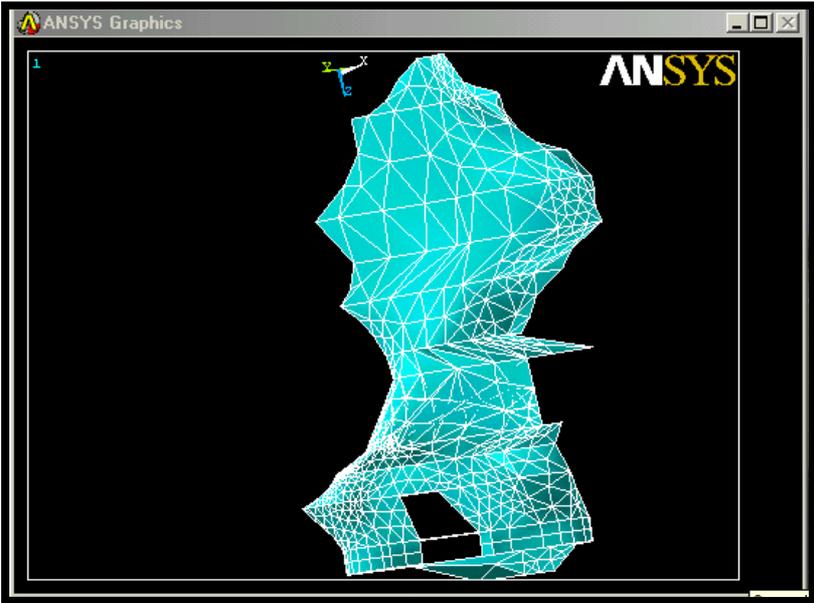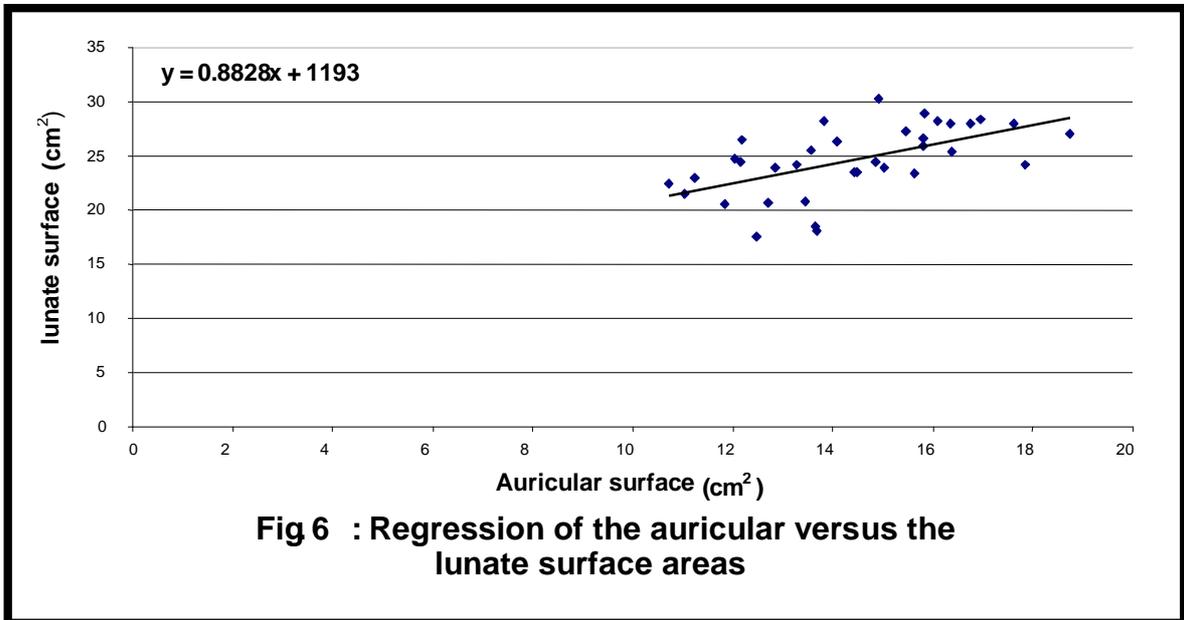
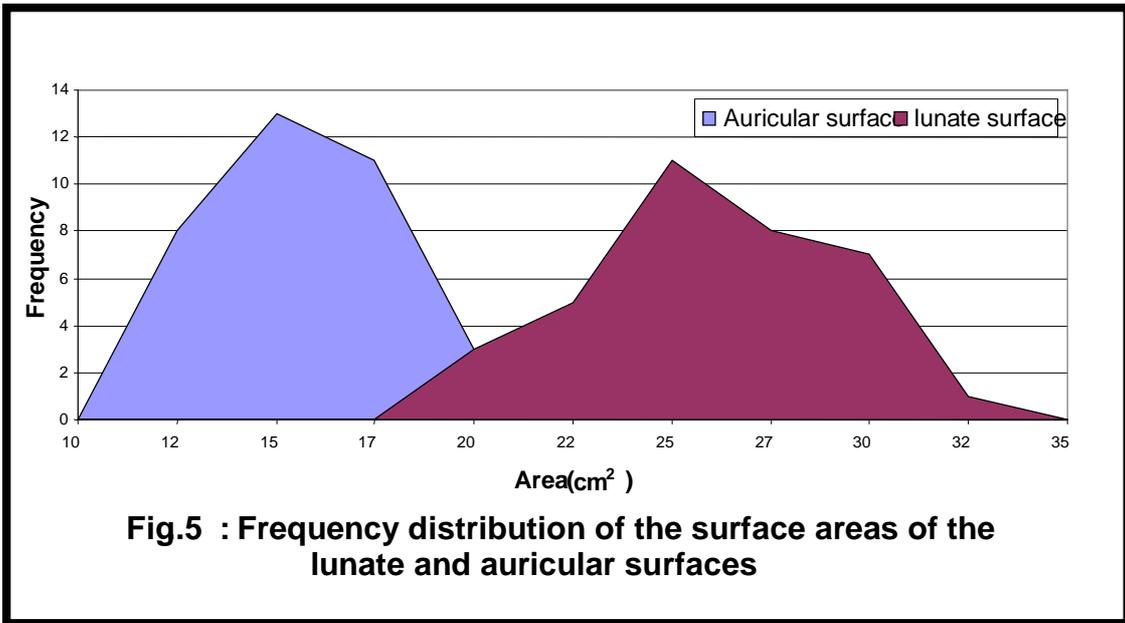**Fig.3 computer screen after the model have been meshed**

Fig.4 accessory sacroiliac joint (arrow)

Fig.5 : Frequency distribution of the surface areas of the lunate and auricular surfaces

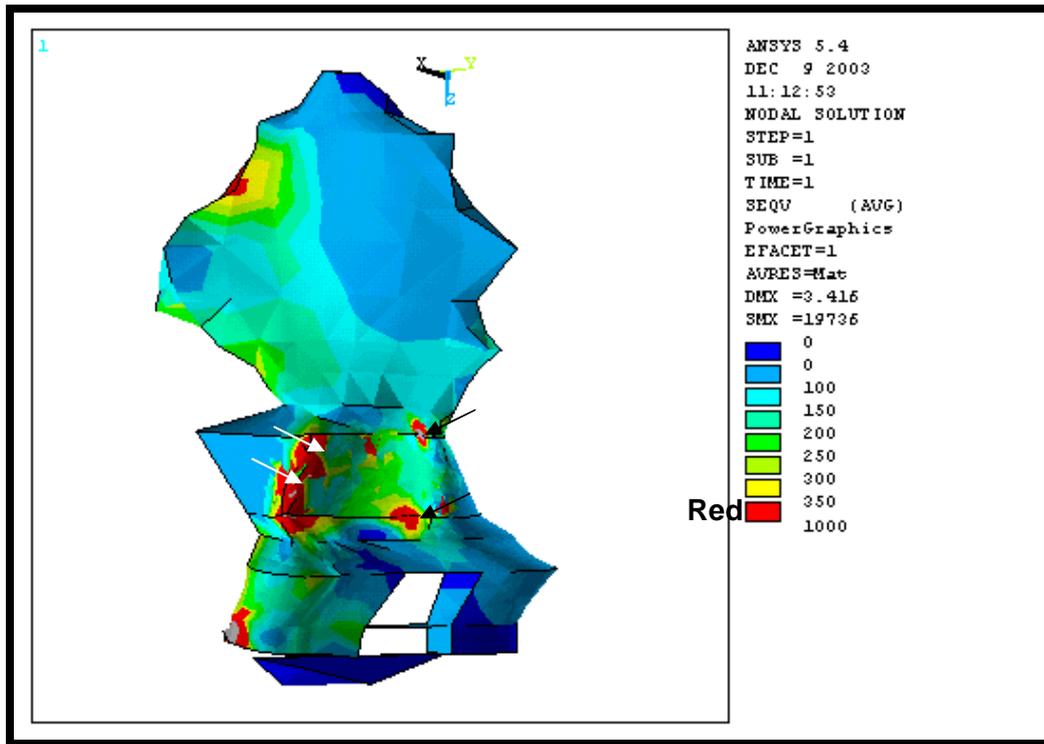Fig.6 : Regression of the auricular versus the lunate surface areas

Fig 7: Von Mises stress distribution on the lateral surface of the hip bone in a 70 kg body by using ASNSYS program for FEA.
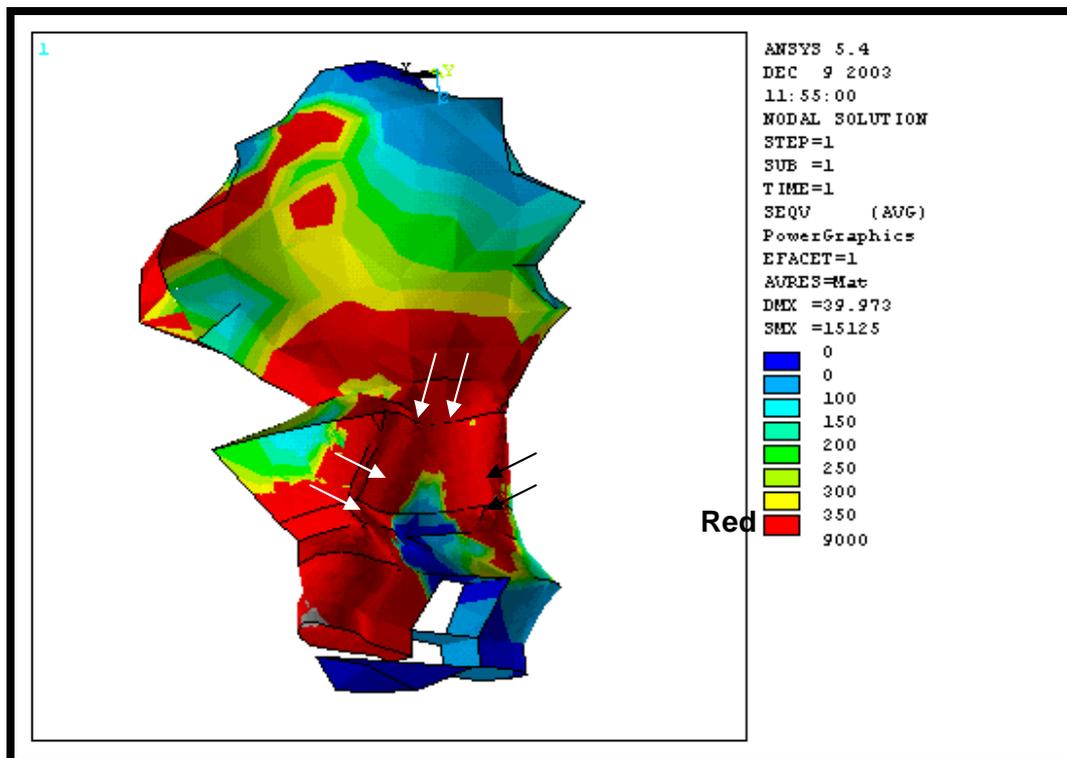

Fig 8: Von Mises stress distribution on the medial surface of the hip bone for a 110 kg body by using ANSYS program for FEA

Conclusion:

Statistical analysis of articulating surface areas indicated that both the lunate and auricular surfaces are involved in force transmission through the hip bone. The symphysis pubis is part of the anterior buttressing arch of the articulating pelvis. Area differences indicated that only 49% of the load reaching the hip bone is being transmitted through the sacroiliac joint. This emphasizes the role of the ligaments which should transmit most of the remaining load. The high stresses at the ischial tuberosity can be attributed to the important role of the sacrotuberous ligament. The sacroiliac joint and acetabular stress values are inversely comparable to their areas

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تحليل الاجهادات في عظم الحوض

د. أكرم عبود جعفر   د. صادق جعفر عباس

هوما محمد عبد الله

جامعة النهرين

الخلاصة:

يلعب عظم الحوض دورا كبيرا في نقل الوزن للأطراف السفلى. ان التعقيد، الشكل الخــارجي، صــفات العظم، والقوى المسلطة عليه تجعل منه موضوعاً مفتوحا لغرض الدراسة والتحليلات البايوميكانيكيه تتعامل هذه الدراسة مع قياس مساحات السطح الاذيني، السطح الهلالي، والارتفاق العاني. أضــافة إلـــى تحليل العناصر المحددة الثلاثية الأبعاد لعظم الحوض لغــرض دراســة القيمـــة، اتجـــاه توزيـــع القــوى، وانتشارالاجهادات تحت الظروف الفسلجيه للجسم.

تم قياس المساحات السطحية للسطح الاذيني، السطح الهلالي، والارتفاق العاني في (٣٥) عظمة حــوض للإنسان البالغ. كما تم تحويل مجسم صلب لعظم الحوض إلى برنامج ANSYS لغرض تحليـــل العناصــر المحددة تحت تأثير القوى المختلفة.

كانت المساحات السطحية للسطح الاذينــي، السطح الهلالــي، والارتفــاق العــاني (٣٩.١٤±٢.٠٥ ,٤٦.٤±١.٠٩ و ٢٤.٦٣ ± ٣.٢) سم٢ على التوالي. ظهر وجود زيادة ايجابية في العلاقة بين الســطح الهلالي والسطح الاذيني، الا ان مثل هذه العلاقة لم تظهر بين السطح الهلالي والارتفاق العاني. عندما تــم تسليط القوى بالنسبة لوزن ٧٠كيلوغرام لتحليل العناصر المحددة للنموذج باستخدام طريقة فون ميســز ظهر بأن الاجهادات تتوزع بشكل رئيسي في تجويف الحــق (الجهـــه الاماميـــة11.2%، العليـــا٤.٥%، والخلفية% ١٥.٩)، السطح الاذيني (% ٢٤.٦) ، والاحدوبة الوركيـــة (٤٠.٣%). أظهــرت النتـــائج أن الاجهادات لوزن اعلى تتناسب تناسبا طرديا مع الأوزان المسلطة. اما فيما يتعلق بالاجهاد الرئيســـي فقــد أظهرت النتائج أن نقاط الفشل سوف تظهر في الجهة الامامية والخلفية لتجويف الحق وكذلك في المفصل العجزي –الحرقفي.

أظهرت التحليلات الاحصائية للمساحات السطحية التمفصلية أن سطح الهلالي والسطح الاذيني يساهمان في نقل القوى خلال عظم الحوض أما الارتفاق العاني فهو جزء رئيسي في الدعامة ألامامية لحزام الحــوض. أضافة ألى أن الفرق في المساحات يدل على ان ٤٩% من القوى التي تصل عظم الحوض تنتقل من خلال المفصل العجزي - الحرقفي وهذا يدل على أن للاربطة دور كبير في نقل الجـــزء الاكبـــر ممـــا تبقـــى. ان الاجهادات الكبيرة التى ظهرت في الاحدوبة الوركية يمكن ان تُعزى الى الدور الكبير الذي يقوم به الربـــاط العجزي الاحدوبي. ان قيمة الاجهادات في المفصل العجزي - الحرقفي و تجويف الحــق تتناســب تناســبا عكسيا مع المساحه.