Al-khwarizmi Engineering Journal

Al-Khwarizmi Engineering Journal, Vol.2, No.1,pp 1-14, (2006)

Biomechanical Aspects of Shoulder and Hip Articulations: A Comparison of Two Ball and Socket Joints

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(Received 6 March 2005; accepted 2 October 2005)

Abstract:-

The shoulder and hip joints though essentially both are ball and socket joints, show structural variability to serve functional needs.

This study aims at revealing some of the structural and functional properties of each of the two joints regarding the factors that contribute to the stability of any joint in the body, namely: bone, ligament, and muscle.

Twenty dried scapula, hip, humerus, and femur were used. The area of the articular surfaces was estimated by molding a sheet of dental wax. Using special graphics software, a novel procedure was described to calculate the area under the curve, which was postulated to indicate the degree of curvature. Tension test was applied using a testometric machine, which was locally modified to suit biological specimens. A finite element analysis was designed to study the articulating bones under different loading conditions.

In the hip joint, the area of the articular surface of the head of the femur and that of the lunate showed no significant statistical difference. For the shoulder joint, the articular areas of the head of the humerus and the glenoid were statistically different. No statistical significance was observed regarding curvature of the articular surfaces within both the hip and shoulder joints; however, the values were significantly different between the hip and shoulder. In the tension test, the site of rupture of the capsule of the shoulder joint was found to be at its anteroinferior part.

The more contact between the area of the cup and ball, as was demonstrated in the hip joint, the more stable the joint. On the contrary, the shoulder articular surfaces have less area of contact, which makes it more mobile and decreases stability. The insignificant difference in curvature within both joints indicates a good congruity and thus more stability especially during joint movement. The curvature difference between the head of femur and the head of humerus indicates that the range of motion is quite different for the two joints. Results obtained from the finite element analysis were important in understanding the areas of stress concentration and were thoroughly explained from the anatomical point of view and linked to muscle and joint capsule attachments. The model of the joints developed in this study can be used as a computational tool to joint biomechanics and to prosthetic implant analysis.

Keywords: hip joint, shoulder joint, finite element analysis, biomechanics.

1.Introduction

The shoulder and hip joints are synovial joints of the ball and socket variety, each is formed of a ball–like convex surface being fitted into a concave socket. Both joints have three degrees of freedom of motion: flexion-extension, abduction-adduction, and rotation. Each joint has a capsule and several associated ligaments. The bones articulating in the shoulder joint are the head of the humerus and the glenoid cavity of the scapula; in the hip joint, the articulating bones are the head of the femur and the lunate surface of the acetabulum of the hip bone[i,ii].

Functionally, the hip joint provides stability in addition to providing mobility; whereas the shoulder provides primarily mobility. The hip joint supports the weight of the head, upper extremities, and trunk in the erect posture. It also provides a pathway for the transmission of forces from the pelvis to the lower extremity and from the lower extremity to the pelvis. Structurally, the pelvis is relatively rigid unitary structure, compared with the freely moveable, independent structure of the scapula[ii]. Thus, these two joints though essentially both are ball and socket joints but they bear structural variability to sub serve functional needs.

The hip and shoulder articulations were the subject of extensive biomechanical studies using a variety of methods[iii,iv,v,vi,vii]. In this study, the shoulder and hip joints will be compared for some structural and functional properties pertaining to bone, ligament, and muscle; the triad that control joint stability. Studying the areas and curvatures of the articular surfaces should reveal some architectural properties pertaining to their stability and range of motion. Tension test would help to unfold some mechanical properties of the joint capsule and associated ligaments. Finite element analysis (FEA) would help to reveal tension and stress pathways across the joints. FEA is one of the modern methods of human joint stress analysis[viii,ix,x,xi]. The aim of the finite element analysis is to develop a three-dimensional model of the joints that can be used as a computational tool to joint biomechanics and to prosthetic implant analysis.

2.Materials and methods

A series of 20 isolated dried scapula, hip, humerus, and femur were used from the inventory of the College of Medicine/ Al-Nahrian University. The bones belong to adults of the Caucasoid race regardless of gender.

Measurement of the area of the articular surfaces

The areas of the smooth articular surface of the head of the humerus, glenoid cavity of the scapula, the head of the femur, and the lunate surface of the acetabulum of the hip bone, which in life would have been covered by articular cartilage were estimated using a molding technique.

A sheet of dental wax was warmed gently until just pliable, molded to the contours of the articular surfaces, and trimmed exactly around the articular margins. The trimmed piece was weighed along with a reference piece of wax sheet of known area. The surface area of the molded wax was calculated from these values[xii].

The curvature of the articular surfaces

Each of the heads of the humerus and femur was digitally scanned using a flat bed scanner. On the scanned profiles, 20-36 points were allocated on the circumference. The curvatures of glenoid cavity and lunate surface were treated by inserting an amount of children clay into the socket, pressed until it took the shape of the socket. The molded clay piece was then processed in a similar manner as indicated for the joint ball.

Using circumference points, a curve was drawn by a Turbo Grapher program (TurboGrapher 32bit, Version 2.135 Copyright ©1996-1999, Jeffrey R. Radue ,P.E) from which the area under the curve was calculated.

Tension test

A testometric machine (Testometric Co. Ltd., England), at the College of Engineering/ Department of Medical Engineering/ Al-Nahrain University, was employed. The machine is originally devised for testing the mechanical properties of materials such as tension, compression, and bending. In this study, hooks and metal holders were designed to modify the machine so that it will be suitable for testing biological material (Fig.1).

Two fresh sheep shoulder joints were used to standardize the machine. Two adult, male, formalin-fixed human shoulder joints were denuded from their muscles with care taken not to disrupt the capsule. The human joints were provided from the teaching material used at the College of Medicine/ Al-Nahrain University.

Tension was applied on the joints to measure the amount of force required before the joint capsule is torn.

3.FEA study using ANSYS 5.4

The bones that were used for model geometry were cut into slices and drawn on a graph paper from which key points were determined. These points were used to make a closed curve which represents the section plane circumference then converting this curve into area. Relations between section planes give the final volume which represents the model. After the creation of the model, it was meshed to be ready for force application and stress analysis. Regarding the hip bone, the model used by Jaffar et al.[xiii] was employed.

Isotropic material properties were used follows: σ_{yield} = 85, $\sigma_{ultimate}$ =120, **E**=18000 (MPa). The weight was regarded as a boundary condition. Segment weights expressed in percentage of total body weight.were used[xiv].

The applied load was represented by the force of muscles and ligaments attached to the bones. These forces were calculated using the basic equation of moment equilibrium ($\Sigma M_P=0$), Where P is the center of rotation. By finding the distance between the center of rotation of each bone and the point of force action, the approximate values of muscle and ligament forces were found.

The major muscles, ligaments and reaction forces acting on the bones[xv,xiv,xvi] were calculated for their forces. For each model, the applied forces were supposing three body weights: 70kg, 90kg, and 110kg (Tables 1-4).

4.Results

Area of the articular surfaces:

In the hip joint, the mean area of the articular surface of the head of the femur was 29.8±1.23cm^2, the mean area of the lunate surface was 24.8±0.75cm^2. In the shoulder joint, the mean area of the articular surface of the head of the humerus was19.0±0.88cm^2 and the mean area of the glenoid cavity was 5.40±0.30cm^2. The difference in the mean areas was statistically significant in the shoulder joint (t-test, $P<0.01$).

Curvature of the articular surfaces

The means of area under the curve of the articular surfaces of the head of the femur, lunate surface, head of the humerus, and glenoid cavity were 140.0±5.837, 141.0±6.505, 87.9±3.488, and 85.9±1.453 unit area respectively. Significant statistical difference existed between the means of the area under the curve of the two joints, while the same parameter did not vary between the ball and socket within the same joint (t-test, $P<0.01$).

Tension test

The testometric machine worked successfully with the sheep material and was standardized accordingly. In the fixed human joints, increasing the tensile force resulted in broken bones before the joint capsule was completely torn. The maximum force reached before the test was stopped was 850N (Fig.2), at this point, however, the shoulder joint capsule was partially torn at its anteroinferior part. Because of bone fragility, the test was not extended for a human hip joint since no human fresh material could be provided.

5.Models Analysis

The results of the FEA were represented as a contour and as von Mises stresses. The color contours represent the range of the stresses, from the blue (low value) to the red (high value). The area with red color is the area at which the stress is in its maximum value and it is the first probable region to fail when the joint is loaded with very high loads. Figures 3-5 show the color contours of von Mises stresses when supposing that 90kg body weight material was used.

For the scapula (Fig.3), the stress concentration was in the spine, scapular notch close to the neck, superior angle and the superior part of the medial border. The stress in these regions increased with the increase of the body weight. Analysis of the scapula for the 90kg and 110kg body weight, revealed that another region of stress concentration could be noted, this was represented by a beam of stresses radiating from the superior-medial aspect toward the inferio-lateral border of the scapula, adding some stresses in the neck and around the glenoid cavity.

In the humerus (Fig.4), the regions that revealed high stresses were the greater tubercle and the surgical neck. The stresses inside the upper end of the humerus if compared with that of the scapula were small.

Regarding the acetabulum, and by using the model of Jaffar et al.[xiii] the largest values of stresses for 70kg person were distributed in its anterior and posterior borders. By increasing the load, it was noticed that stresses would be concentrated in the superior part of the acetabulum.

In the femur (Fig.5), the stresses were concentrated at the upper part of the head and neighboring part of the neck at all loading conditions. A line of high stress can also be noted at the lower margin of the neck. The neck of the femur, however, demonstrated higher stresses than the lower part of the head and the regions of the greater and lesser trochanters. The stresses of the upper end of the femur were higher than those recorded for the scapula or the upper end of the humerus.

6.Discussion

Factors that contribute to the stability of any joint in the body are bone, ligament, and muscle[ii]. In this study, the role of the bony articular surfaces in maintaining joint stability was studied measuring the area of the articular surfaces and calculating the degree of curvature.

Areas and curvatures

The wax technique method used to measure the area of articular surfaces was simple and required no expensive equipment; it could be applied particularly to the area measurement of highly curved articular surfaces.

The mean of the areas of articular surfaces of the hip joint did not differ significantly, while the difference was statistically significant for the shoulder joint. The difference in areas of the articulating surfaces gives an indication of the degree of compatibility of the ball with its socket. The ratio of the area of articulation of the femur to the lunate was (1.2:1). For the shoulder joint, the ratio of the area of articulation of the humerus to the glenoid of the scapula was (3.5:1). The ratio between the areas of each ball with its socket was comparable with that of the other researchers[xv]. The more contact between cup and ball, the more stable the joint is. From the above-mentioned ratios, the hip is more stable than the shoulder joint. The greater mobility of the shoulder increases instability and the risk of dislocation.

Another parameter that plays a role in joint stability pertaining to the bony factor is the curvature of articular surfaces. It is difficult to measure the curvature of the articulating surfaces and there was no applicable nor a standard method to measure it in biological specimens. Thus, a simple yet applicable method was used in this study to find a value that represents the curvature; that is the area under the curve.

The effect of curvature – as a parameter or property – indicates the degree of congruity of the articular surfaces of a joint. In this study, where there was no significant difference in curvature within both joints, it can be concluded that there was a good congruity of the joint articular surfaces. Congruity implies more stability especially during joint movement. The effect of congruity of joint surface has a less profound significance in static state.

The significant difference in curvature between the two balls (the head of hip and the head of humerus) and between the two sockets (glenoid cavity and the lunate surface) indicates that the range of motion is quite different for the two joints.

It should be emphasized that the results of this study does not take into account the shape and thickness of the articular cartilage nor the presence of the fibrocartilagenous labrum that surrounds the socket of both joints.

Tension test

The modifications applied to the testometeric machine in this study (hooks and metal plates) were suitable for joint installation as has been proved by the pilot study on the sheep joint. However, formalin fixed human bone could not withstand the forces applied. Formalin fixation changes the tensile properties of collagen and renders the bone weaker and easy to be broken[xvii]. It is recommended that the modified machine be used on fresh tissue. Since no fresh human hip joint could be afforded then the test was not extended to the hip joint. Future studies on the modified machine can implement fresh animal joint when no human material can be provided.

In spite of the bone failure when testing the human shoulder joint, the force which was applied before failure was 43% of the desired force and the curve obtained was comparable to the curve of Kaltsas in shoulder joint[xviii]. The site of rupture of capsule of the shoulder joint was at its anteroinferior part suggesting that this part of the capsule is the weakest. This corresponds to the finding that anterior dislocation of the shoulder is the most common as is always mentioned in literature[xix],[xx].

FEA models

In the scapula where the stress which was concentrated in the scapular spine and the region of scapular notch close to the neck can be attributed to the tensile force applied from the upper fibers of trapezius muscle. In the superior angle and the superior part of the medial border of the scapula, the effect of the levator scapula and rhomboid minor was the major force which causes the reactions and stresses in this region.

The stresses in the neck of the scapula and around the glenoid cavity for the 90kg and 110kg body weight analyses, can be attributed to the reaction between the upper medial border at which the upper trapezius and the levator scapula muscles try to elevate the scapula upward, and the infero-lateral border at which the load applied is represented by the weight of the upper limb which pulls the scapula inferiorly.

In the greater tubercle of the humerus, the high stress can be viewed as a translation to the effect of the force of the joint capsule and the coracohumeral ligament, but above all, to the rotator cuff muscles. These muscles stabilize the joint by pressing the head into the glenoid. Three of the four rotator cuff muscles (namely, supraspinatus, infraspinatus, and teres minor) are attached to the greater tubercle very close to the attachment of the capsule of the shoulder joint for which they provide reinforcements[xxi].

At the surgical neck of the humerus (the narrow region between the proximal end and the shaft of the humerus, which is the most likely region to be fractured in the upper part of the humerus[xxii]), stress concentration reflected an internal interaction between the loads applied on the humerus (represented by the weight of the rest of the humerus plus the weight of the forearm and hand) and the reaction force on the articular surface of the humerus, the tension force of the joint capsule, and rotator cuff muscles.

The small stresses inside the upper end of the humerus when compared with that of the scapula might be attributed to thinness of the latter bone. However, the fact that only the proximal end of the humerus was analyzed in this study should not be overlooked. The forces that suspend the humerus are not only concentrated at its proximal end, but there are other powerful muscles that suspend the humerus yet they have a more distal insertion. These muscles are the coracobrachialis and deltoid, which are attached to the middle of the shaft of the humerus (a region which was not included in this study). Moreover, biceps brachii, another muscle suspending the upper limbs in the static position, is not attached to the humerus but to the more distal radius. The long head of triceps, which extends from the scapula to the ulna, suspends the limbs at a more distal position than the humerus[xxi].

The intact acetabulum is a horseshoe form that wraps around the superior, anterior, and posterior aspects of the femoral head. In the lightly loaded state for the 70kg, the dome of the acetabulum is relatively unloaded, and the stress is transferred between the femoral head and the acetabulum through the anterior and posterior extensions of the horseshoe[iii]. When the load was progressively increased (for the 90kg and the 110kg body weight) and 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.

In the femur, where stresses higher than the humerus and scapula were recorded, this is coexistent with the fact that the weight-bearing femur is subjected to higher force if compared with the applied load on the humerus and scapula. The concentration of the stress at the upper part of the head is consistent with the finding that pressure distribution in the articular cartilage is mainly concentrated in its anterosuperior surface when using pressure-sensitive film[iii]. The concentration of these stresses at the neck of the femur even in the slightly loaded state explains the predilection of the neck to undergo fracture. In older subjects, femoral neck fractures, which are common, might take place even after mirror tripping[xxii]. The line of high stress at the lower margin of the neck is compensated in life by the calcar femorale, a flange of compact bone projecting like a spur into the cancellous bone of the neck and adjoining shaft from the concavity of their junction[xxiii].

Body weight (kg)	Weight of arm, forearm and hand (N)	Upper Trapezius (N)	Levator scapulae (N)	Rhomboids (N)
70	39.6	44.5	34.6	19.8
90	50.9	57.3	44.5	25.4
110	62.2	69.9	54.4	31

Table (1) Calculated forces acting on the scapula

Body weight (kg)	Weight of forearm & hand (N)	Coracohumeral ligament force (N)	Reaction force (N)
70	28.5	12.2	4
90	36.6	15.7	5.2
110	44.7	19.1	6.4

Table (2) Calculated forces acting on the humerus

Body weight (kg)	1/3 of B.W (N)	Abductor muscles (N)	Reaction of ground (N)
70	228.7	22.9	68.6
90	294	29.4	88.2
110	359.3	35.9	107.8

Table (3) Calculated forces acting on the femur

Body weight (kg)	1/6 of B.W (N)	1/3 of B.W (N)	Force of Sacrotuberous ligament. (N)
70	114.4	228.7	63
90	147	294	81
110	179.7	359.3	99

Table (4) Calculated forces acting on the hip bone

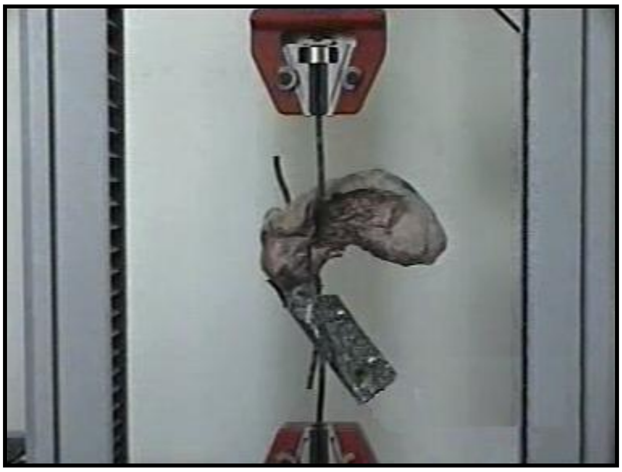

Fig.1: Reinforced human shoulder joint specimen positioned on the testometric machine. Note the metal plate and hooks used to fix and reinforce the specimen.

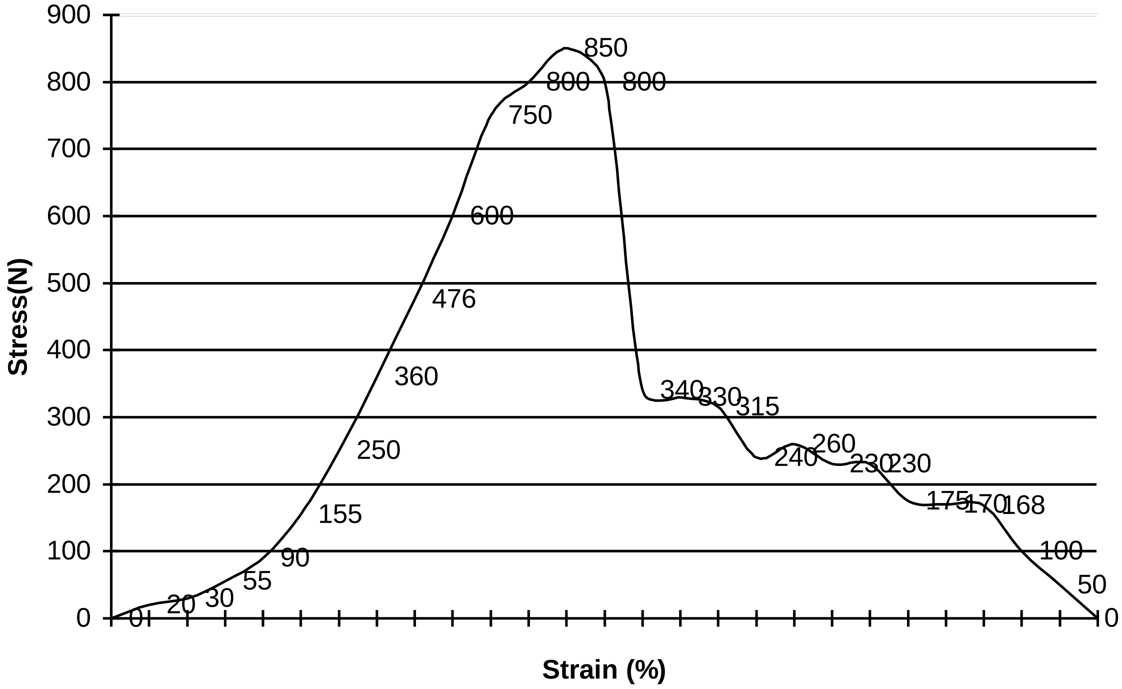

Fig.2: Tension test curve of fixed human shoulder joint. Testometric machine output curve.

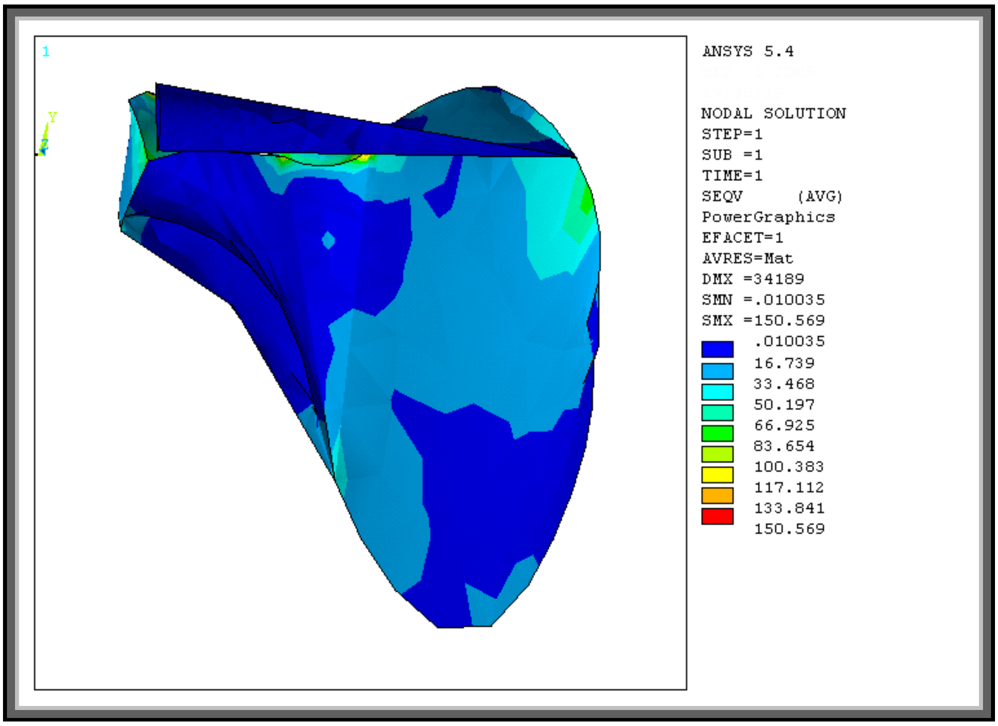

Fig.3: von Mises stresses for 90kg body weight of the posterior surface of the scapula.

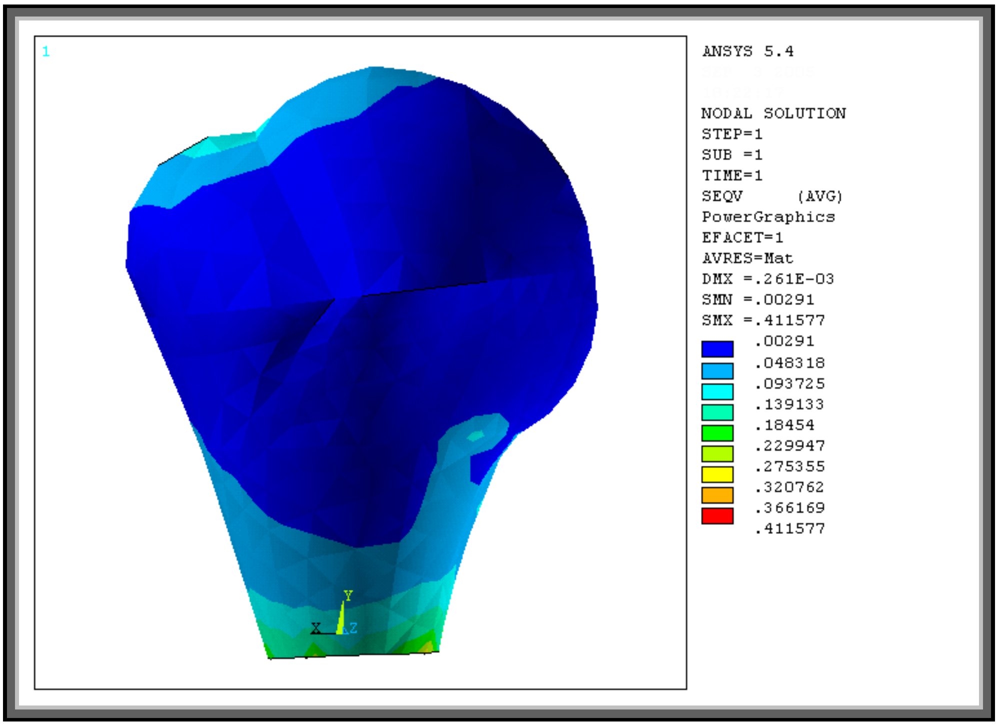

Fig.4: von Mises stresses for 90kg body weight of the posterior surface of the Humerus.

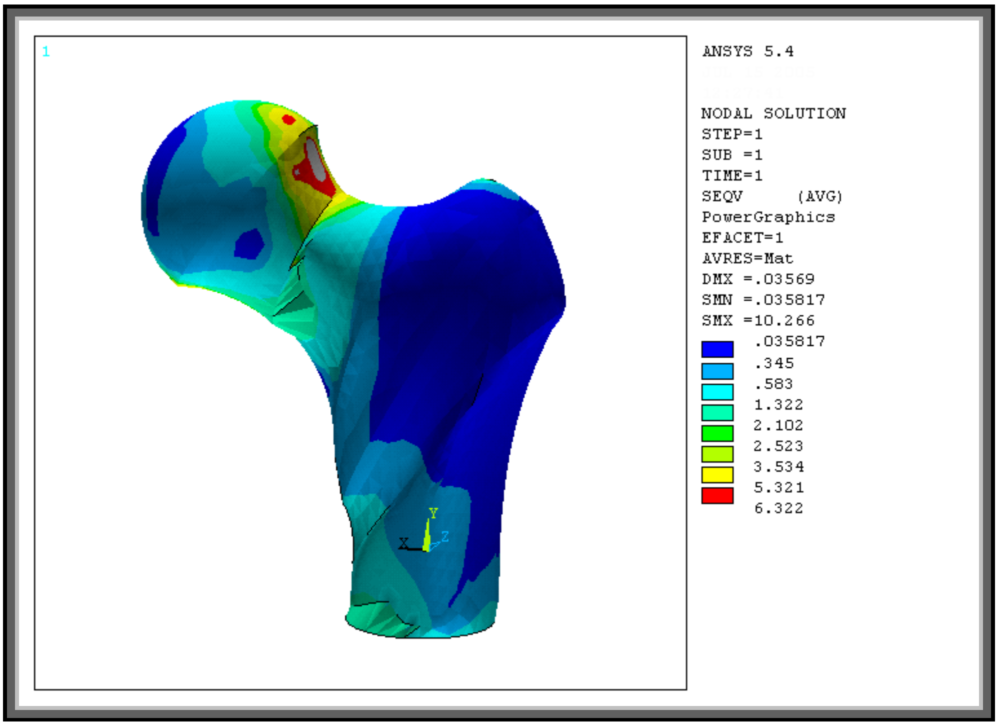

Fig.5: von Mises stresses for 90kg body weight of the posterior surface of the Femur.

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جوانب ميكانيكية احيائية لتمفصلات الكتف والورك: مقارنة لمفصلين من نوع الكرة والتجويف

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الخلاصة:

رغم ان مفصلي الكتف والورك ينتميان اساساً الى نوع المفاصل ذات الكرة والتجويف الا انهما يظهران تباينات تركيبية لخدمة المتطلبات الوظيفية. تترافق هذه الاختلافات التركيبية بين المفصلين بالضرورة مع الخواص الميكانيكية التابعة لأي منهما.

تهدف هذه الدراسة الى الكشف عن بعض الخواص الميكانيكية والوظيفية لكل من مفصلي الورك والكتف. حيث تم سبر الخواص الهندسية التصميمية لسطوح التمفصلات العظمية من خلال دراسة مساحة وتقوس هذه السطوح. كما تم استخدام فحص الاجهاد للكشف عن بعض الخواص الميكانيكية لمحافظ المفاصل والاربطة المرافقة لها. كما تم استخدام نموذج لغرض تحليل العناصر المحددة لاظهار مسارات الشد والضغط عبر المفصلين.

تم استخدام عشرين عظم جاف من كل من لوح الكتف، الحوض، العضد، والفخذ. وتم حساب مساحات التمفصل باستخدام قالب من شمع الاسنان. كما تم وصف طريقة مبتكرة لاحتساب المساحة تحت التقوس عن طريق استخدام برامجية خاصة للتعامل مع الرسوم. ونعتقد بأن هذه الطريقة يمكن ان توفر مؤشر لدرجة التقوس. كما التجأنا الى تحوير جهاز فحص الاجهاد محلياً ليتلائم مع فحوصات النماذج البايولوجية. اما دراسة تحليل العناصر المحددة فقد صممت بعد تقطيع العظام الى شرائح وتحويلها الى صور رقمية ثلاثية الابعاد ليتم تحليلها بواسطة برنامج Ansys تحت تأثير قوى مختلفة.

اظهرت النتائج في مفصل الورك بأن مساحة السطوح التمفصلية لرأس عظم الفخذ والسطح الهلالي لم تكن مختلفة احصائيا (٢٩،٨±١،٢٣ سم^{٢} و ٢٤،٨±٠،٧٥ سم^{٢} بالتتابع). اما بالنسبة لمفصل الكتف، فأن السطوح التمفصلية لرأس عظم العضد والجوف الحقاني اظهرت اختلافا احصائيا (١٩،٠±٠،٨٨ سم^{٢} و ٥،٤±٠،٣ سم^{٢} بالتتابع).

كانت المساحة تحت التقوس للسطح التمفصلي لرأس عظم الفخذ والسطح الهلالي ١٤٠،٠±٥،٨٤ و ١٤١،٠±٦،٥١ وحدة مساحة بالتتابع. اما في مفصل الكتف فقد كانت القيم لراس عظم العضد والجوف الحقاني ٨٧،٩±٣،٤٩ و ٨٥،١±١،٤٥ وحدة مساحة بالتتابع. لم تلاحظ فروق احصائية مهمة ضمن مفصلي الورك والكتف، في حين كانت الفروق مهمة احصائياً عند المقارنة بين سطوح المفصلين.

تمت مناقشة الصعوبات التي واجهت تطبيق فحص الاجهاد وذلك لجعل الآلة المستخدمة اكثر ملائمة للفحوص البايولوجية في المستقبل. ورغم الصعوبات الا ان النتائج اظهرت بأن موقع تمزق محفظة مفصل الكتف كانت عند الجهة الامامية السفلى.

ان وجود تماس كبير بين مساحة الكرة والتجويف، كما ظهر في مفصل الورك، يجعل المفصل اكثر استقراراً. على العكس من ذلك، فان مساحة التماس للسطوح التمفصلية لمفصل الكتف كانت اقل بكثير مما يقلل من ثبات المفصل.

ان عدم وجود فروق مهمة لتحدب السطوح التمفصلية ضمن مفصلي الكتف والورك يشير الى جودة التطابق وبالتالي ثباتاً اكبر خاصة عند حركة المفصل. اما اختلاف التحدب بين المفصلين فانه يشير الى اختلاف مديات الحركة بينهما.

كانت النتائج التي تم التوصل اليها من خلال تحليل العناصر المحددة مهمة في تحديد مناطق تمركز الاجهادات وقد تم تفسيرها من وجهة نظر تشريحية وربطها بمناطق اتصال العضلات ومحفظة المفصل. ان نماذج المفاصل التي طورت في هذه الدراسة يمكن ان تستخدم كوسيلة حساب للميكانيك الاحيائي للمفاصل وفي تحليل المفاصل الصناعية المغروسة.

مفتاح الكلمات: مفصل الورك، مفصل الكتف، تحليل العناصر المحددة، الميكانيكا البيولوجية