ORIGINAL PAPER

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Abductor weakness and stresses around acetabular components of total hip arthroplasty: a finite element analysis

Accepted: 24 August 1999

Abstract Abductor weakness, and the resulting Trendelenburg gait, after total hip arthroplasty is believed to be associated with a poor long-term outcome. We have constructed a two-dimensional finite element analysis using load cases to mimic this abductor weakness. The finite element analysis demonstrates slightly increased stresses, particularly at the bone-cement interface in the DeLee-Charnley zone I, which does not seem sufficient to explain the adverse effect of abductor weakness.

Résumé L'affaiblissement des muscles abducteurs et la démarche qui en résulte après le remplacement de la hanche par prothèse, peut être associé avec un résultat médiocre à long terme. Nous avons réalisé une étude par éléments finis à deux dimensions avec des situations imitant cette faiblesse des muscles abducteurs. Cette analyse montre une augmentation légère des contraintes particulièrement à l'interface os-ciment dans la zone I de DeLee et Charnley. Ceci ne semble pas suffisant pour expliquer les effets défavorables de l'affaiblissement des abducteurs.

Introduction

Since the introduction of cemented low friction total hip arthroplasty (THA) for osteoarthritis of the hip by Sir John Charnley in 1960 [4], attempts have been made to improve upon his original results. Many new prostheses

have appeared on the market, but only a small number have been shown to have equivalent long-term results to the Charnley prosthesis [15]. Second generation cementing techniques have improved survival of femoral components of THA, but not of the acetabular component [1,12,16]. Attempts to solve this problem have addressed factors such as the cementing technique, use of key holes, the position and orientation of the prosthesis relative to the normal anatomic position, and the importance of abductor muscle function. It has been suggested that abductor weakness, which may be a consequence of osteoarthritis or of the surgical approach utilized, may result in increased force concentration and more rapid wear and loosening of the acetabular component. Abductor weakness leads to relative adduction of the leg with resultant force transfer through a more vertically aligned acetabular component. It has been determined that in a healthy body the hip reaction force is typically 17° to the vertical [11]. We have undertaken a finite element analysis of stresses at the critical bone cement interface of an acetabular cup when located in the acetabulum, with differing load scenarios mimicking the more vertical orientation of the hip resultant force, in an effort to determine the effect of abductor weakness.

Materials and methods

A two-dimensional (2-D) finite element model has been developed on ANSYS software (Swanson Analysis Systems Inc, Houston, Pa., USA) to determine whether there is a link between the direction of loading of the acetabular cup and stress concentration, which may lead to cup loosening. The model used in this investigation was a simplified representation of the system under investigation to establish the viability of further studies.

The model consisted of the acetabular cup (the style of cup used in this model was a standard ultra high molecular weight polyethylene (UHMWPE) acetabular cup with an inner diameter of 28 mm, outer diameter of 40 mm and was 180° open), a 4 mm layer of cement (between the subchondral bone and cup) [2], subchondral bone and cancellous bone. Keyholes through the subchondral bone, into the cancellous bone and filled with cement were also represented in the model. The cup was oriented at 30° to the vertical axis [10].

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Fig. 1 Detail of mesh developed

Table 1 Material properties

	Young's modulus E (GPa)	Poisson's ratio γ
Acetabular cup	1.0	0.4
Cement	2.5	0.3
Subchondral bone	17	0.3
Cancellous bone	0.7	0.3

The model consisted of 2-D, 8-node solid elements, with the mesh developed from 5° element edge lengths on the inner surface of the cup and developed from this surface into the acetabulum taking care to avoid sudden changes in density (Fig. 1.), with computing power limitations defining mesh detail. Loading was applied over a 60° contact area with the force resolved into 12 components at 5° divisions, to coincide with the nodes. Constraints were applied in the Y-direction on the two surfaces. In this investigation a number of different load cases were investigated. The highest force experienced during normal gait is 7 times body weight, and, assuming a 75 kg male, this force would be 5150 N: a force of 500 N was adopted. This force was resolved into two components (X and Y) at 2.5°, 12.5°, and 17.5° from the vertical axis.

It was assumed that there was no friction or adhesion between the components and, thus, no shear forces between components. For this reason, on these surfaces no specific contact elements were included, since the ANSYS package has a facility that recognizes coincident nodes of different components. Other assumptions were made in the development of the finite element model were that bone is a linear, isotropic material, that all materials adhered to Hooke's law and that frictional forces could be ignored. These simplifications were adopted to limit constraints due to computing power, in keeping with previous work. This allowed generation of Von Mises stresses, which represent the average principal shear stress at each element [10,19].

Material properties used in this model were taken from those currently used by investigators in this field [10] and are summarized in Table 1. Young's modulus of elasticity is denoted by E, while γ denotes Poisson's ratio, a constant that relates to the ratio of lateral to axial strain of the material.

Fig. 2 Load case 2.5°

Fig. 3 Detail of edge of zone I for load case 12.5°

Results

The model was executed for each of the load cases described and the results of Von Mises stresses are presented. These demonstrate the average of shear stresses in both X and Y directions at a point, giving a value that has magnitude but not direction. The results of each of

Fig. 4 Detail of edge of zone I for load case 17.5°

the load cases are described in turn, and are presented as plots in Figs. 2–4. The magnitude of Von Mises stresses increase slightly as the angle of application of the load increases due to the increase in value of the stress component in the Y direction. The area around the bone-cement interface in Charnley-DeLee zone I has been examined in more detail, and results for this region are presented.

Load case 1: 2.5°

Von Mises stresses can be observed as being high at the keyhole in the cancellous bone and the areas from the keyhole to the point of loading (on the cup), and also vertically upwards from the keyhole into the ilium. The magnitude of stress, from the area of high stress, diminishes rapidly and the remaining areas of both the cup and cement layers show relatively low stress values. The peak stress at the bone-cement interface, at the edge of the model in DeLee and Charnley zone I was 105376 N/m².

Load case 2: 12.5°

At the point of application of loading and at the cement bone interface, directly above this point, high stress values were again recorded. The magnitude of stress recorded on the vertical face and into the ilium is reduced from the previous load case with stresses up to a value of 99016 N/m².

Load case 3: 17.5°

A similar stress pattern to the 12.5° case was observed, with high stress values on the inner diameter if the cup at the point of loading and at the subchondral bone cement interface. Stress values on the vertical face of the model fell further to 96276 N/m², which represents a decrease of 8.3% from the 2.5° load case.

Discussion

Previous studies have assumed a constant orientation of loading upon the acetabulum close to the supero-anterior quadrant [22], emphasizing the importance of acetabular coverage to transmit these forces without stress concentration. The cement mantle thickness [2] and the stiffness of the acetabular component [17] have been shown to be important in distribution of stresses. Work that has previously looked at the effect of poor functioning of the abductor muscles after THA has suggested that it may be associated with a poor outcome, in addition to a Trendelenberg limp [6,8]. This especially so when the acetabular prosthesis is placed laterally in relation to the center of rotation. Functional impairment of the hip abductors, and the resulting Trendelenburg gait, will lead to adduction of the leg during gait, and effectively a more vertically placed acetabulum, which has been shown to be associated with increased osteolysis [21]. The effect of abductor weakness, however, is to alter the resultant loading of the acetabulum, moving the hip rotation laterally. It does not appear that the choice of surgical approach to the hip affects the functioning of the abductor muscles [9,18].

From our results it can be seen that as the center of rotation is moved towards the center of the body the stresses on the vertical face of the model at the bone-cement-cup interfaces are reduced slightly, with a decrease of 8.3% between the 2.5° and 17.5° load cases. The magnitudes of stresses in all load cases do not exceed the yield or ultimate values of any of the materials although with repetitive/cyclic loading at the higher stress levels there may be a risk of fatigue failure. Stress patterns vary as a result of changing the position of the load, and therefore remodeling of the bone will take place as a result of the alteration of loading conditions from the original hip. The 17.5° load case is closest to loading in a “healthy” hip [13].

Host responses to polyethylene particles are known to be at least in part responsible for osteolysis around the THA [7,14,20], and failure of the bone cement interface allows ingress of wear particles, contributing to further loosening of the cup. The area that is of most concern is the face leading up to the ilium, Zone I of DeLee and Charnley’s system [5], where the majority of osteolysis is found [23], making stresses at this position of particular interest. While the greatest stresses are seen at this site in our model of abductor weakness (load case 2.5°), the differences between this case and the 17.5° case may

not be sufficient to explain the problems associated with abductor weakness.

As this is a 2-D analysis loading of the cup takes place in two planes that does not compare entirely realistically with the complex loading of the hip both from loads transmitted through the femoral head and also muscular forces. This investigation assumed a static load whereas the loading of a hip is dynamic. The results of the investigation illustrate possible areas where further research on acetabular loosening would prove valuable, i.e. in the development of a 3-dimensional model initially with similar loading applied, followed by a dynamic loading study. While such finite element studies provide some useful information on stresses in the THA, they must be interpreted with caution. Previous work has suggested that the most favorable stress conditions were created when a metal-backed acetabular prosthesis was used [2,3], but this has not been borne out in clinical experience. Attempts to reproduce such work on specimen acetabulae is also made difficult by the differences found in stress distribution between isolated acetabular preparations and complete pelvic preparations [17]: it is difficult to control for the complexities of the complete biological system that is the hip joint. The rapid advance of computing technology may allow more accurate modelling of this system in the future.

The investigation was successful in highlighting areas of higher stress in the acetabular component of a THR under the conditions that may exist in a patient with abductor weakness and Trendelenburg gait. The increased stresses that develop upwards from the cup to the ilium demonstrate areas of concern that coincide with the areas that surgeons believe to be the initiation point of cement breakdown, but the stresses demonstrated are small, and further work is required to examine the effects of abductor weakness.

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