Total hip replacement: Improving cement fixation of the acebular component

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Introduction

Total hip replacement (THR) has enabled at least 90% of the patients with deteriorated hip to live normal, pain-free lives for at least 10 years after the operation [1]. Approximately 40,000 total hip replacements are carried out in the UK every year and represent a substantial annual resource cost of about £140,000,000 to the National Health Service of the UK[2]. These figures are expected to increase with the ageing population. Revisions, being more complex than primary THRs, have lower survival rates [3] and can be two to three times more expensive than a primary THR for which the average cost is over £4,000 [2]. Failure of the acetabular component increases exponentially ten years following surgery [4]. Research on new developments of THR is prerequisite to improve the longevity of the implant.

During the cement fixation of the acetabular component, anchorage holes are drilled in the acetabulum to improve the resistance to torque forces of the cup fixation. Torsional resistance depends on a number of factors affecting stress distribution in the cement mantle. These include the geometry [5] and distribution [6, 7, and 8] of the anchorage holes as well as the removal or maintenance of the subchondral bone [9]. A survey of current practice, carried out by the authors, on the fixation of the acetabular component in THR in the UK in 1999 indicated wide variations in the preparation of the acetabulum prior to cementation [8].

The primary aim of this study was to propose fixation techniques that would improve the cement fixation of the acetubular cup. This was done by (1) studying current practice, (2) creating FE models of the reconstructed acetabulum to predict improved fixation techniques, (3) validating the FE models by laboratory investigations and (4) proposing designs of jigs and drill bit that would assist orthopaedic surgeons use the recommended techniques.

Methods

Finite element methods

Initially, two-dimensional (2D) finite element (FE) models of the reconstructed acetabulum with the following geometries of anchorage holes were created: (a) straight, (b) tapered, (c) chamfered, (d) with decreased depth and (e) inclined at an angle to the acetabulum [5]. 2D FE models were also created to study the effect of removing the subcondral bone [9]. Three-dimensional (3D) FE models compared stress values when (a) three 8 mm diameter straight anchorage holes (b) six 1mm diameter straight anchorage holes and (c) three 8 mm rounded anchorage holes were drilled in the reconstructed acetabulum models [7].

Table 1: Material properties of components

Part	E(GPa)	γ
Cancellous bone	0.05	0.2
Subchondral one	1.15	0.3
Cement	2	0.3
Acetabular cup	0.7	0.3
Femoral head	200	0.28

Values of Young's modulus (E) and Poisson's ratio (γ) for bone were retrieved from literature [10,11] (table 1). A total compressive force of 2.2 KN at an angle of 45° [12,13], and a torque of 1 Nm [14] were applied to the reconstructed hip joint. Non-linear static analyses were run on the FE models to compare results of the different models.

Laboratory investigations

Laboratory investigations were carried out on tensile testing machines, to validate the FE models. Reconstructed Shetland pony acetabula with different geometry and distribution of anchorage holes were positioned at 45° to the direction of vertical compressive loading of 2.2 KN, acting at a rate of 50 N/s, by means of specially manufactured jigs and fixtures. Torque was then applied to failure at a rate of angular displacement of 0.5°/s.

Results

Finite element analysis

Results of finite element analyses showed that the regions around the neck of a straight anchorage hole were subjected to high principal stress values, around 40 N/mm2, and poor stress distribution [5]. The value of principal stress near the neck of the cement peg of:

1. at 10° tapered hole is 10% less than that of a straight hole,

2. at a 45° chamfered hole is 18% less than that of a straight hole,

3. a chamfered and a straight anchorage hole with depth reduced from 10 mm to 5 mm increase by only 4% to 5%,

4. an anchorage hole inclined at 10° is 6% higher than that of a hole drilled perpendicularly to the acetabulum [5],

5. is 1.4 % higher when the subchondral bone is removed than when it is maintained, but stress is transmitted in a non-physiological manner [9] and

6. a reconstructed acetabulum with six 4 mm diameter anchorage holes is 130 % higher than one with three 8 mm diameter anchorage holes [7].

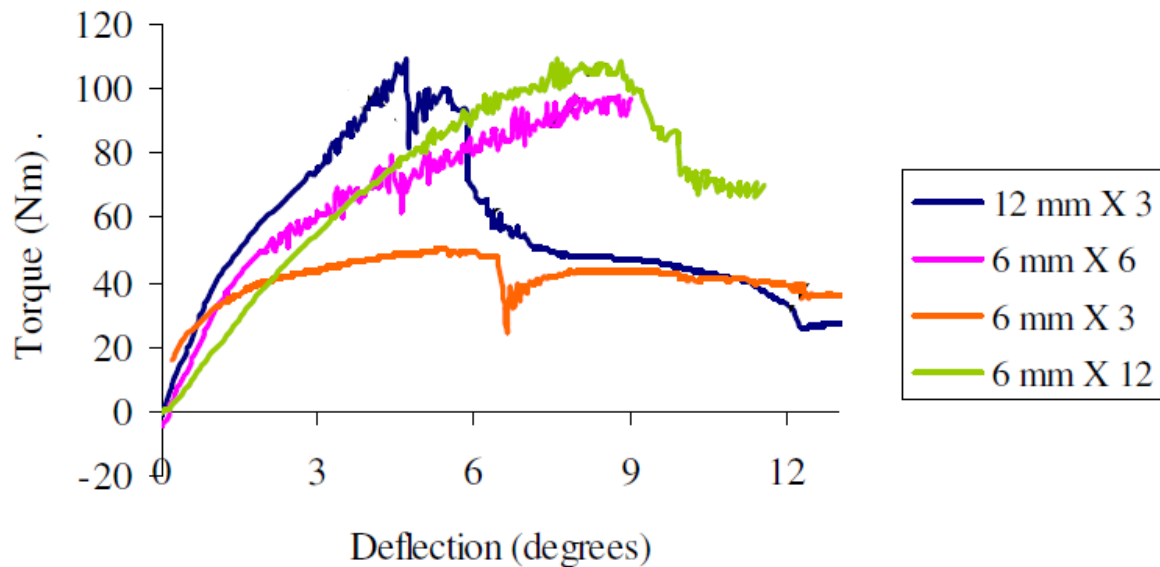*Validation by laboratory investigations*

Fig. 1: Graph of torque v/s deflection for reconstructed acetabula with different distributions of anchorage holes.

Results obtained by laboratory investigations were in line with those obtained by FE methods [8]. Average peak torque to failure for a chamfered hole was more than twice that for a straight hole of similar surface area. Average peak torque to failure for three 12 mm diameter anchorage holes was 13% higher than that for six 6 mm diameter anchorage holes. Typical graphs of torque v/s angular displacement are shown in figure 1.

Proposed drill it and jigs to improve fixation

Based on the above results, a chamfered drill bit, with cutting depth equal to diameter, was designed to create the desired geometry of anchorage holes (Fig. 2). A special jig was designed to assist orthopaedic surgeons drill three large anchorage holes perpendicular to the floor of the acetabulum during a THR (Fig. 3) [15].
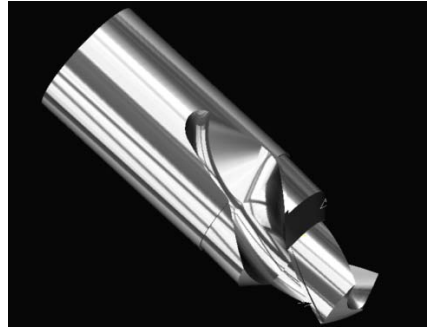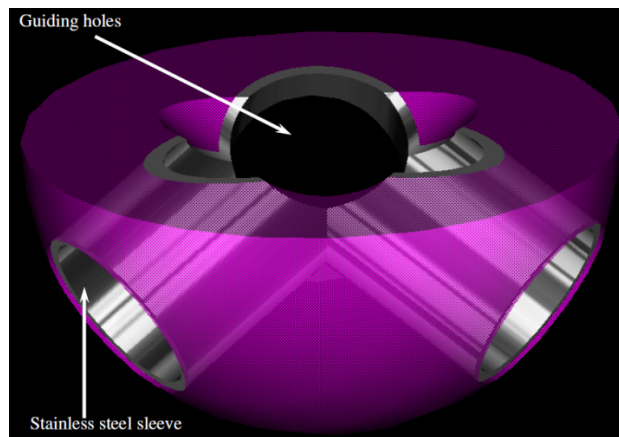
Fig. 2: Proposed drill bit

Fig. 3: Proposed Jig

Discussion

Since this was a comparative study to investigate the relative performance of different methods of fixation, (1) bone material properties were assumed to be homogeneous and isotropic and (2) static, rather than dynamic, finite element studies and laboratory investigations were carried out.

In practice, fracture of the cement mantle usually occurs at the neck of the cement plug due to fatigue. This corresponds to high stress values observed around the neck of the cement peg in the finite element studies and failure of the cement pegs during laboratory investigations. Principal stresses of values around 40 MPa generated at the neck of the cement peg are within the ultimate stress values of commercially available bone cements (31.7 MPa to 51.4 MPa) [16]. It is therefore important to investigate techniques to reduce the stress levels in the cement mantle.

Our results show that increased depth does not improve fixation. This is in agreement with results obtained by Mburu et al. (1999) [6]. In fact, long anchorage holes are subjected to a larger bending moment than shorter pegs. Results obtained from experimental investigations regarding the shapes and number of anchorage holes agreed with those from finite element analyses, confirming that three large anchorage holes with chamfered geometry increase the torque resistance at the bone-cement interface. Our laboratory investigations show little increase in resistance to torque when the number of anchorage is increased from 6 to 12

(Fig. 2). This agrees with the work of Chen and co-workers [17] and Mburu and co-workers [6], but contradicts the modern cementing techniques and the methods used by Ranawat and co-workers [18, 19]. Our results also contradict the conclusions reached by Oh [20]. Had Oh calculated the surface area of the anchorage holes, instead of the cross-sectional area, while devising the configurations of number and geometry of anchorage holes, his results would have been close to ours. Higher stresses are generated when anchorage holes are not drilled perpendicularly to the acetabulum. The proposed jig should overcome this problem.

Our findings indicate the importance of maintaining the subchondral bone and agree with those of several experimental [21, 22, 23] and finite element studies [24,25] but contradict the work of Volz and Wilson[26] and Sutherland and co-workers [27]. Volz and Wilson used inconsistent number of anchorage holes in their study. Sutherland and co-workers assigned a value of 17 GPa to the Young's modulus of subchondral bone which is more than one order of magnitude higher than the 1.3GPa reported in earlier publications [10,11]. This could explaine the overestimation of their result on percentage reduction in stress when the subchondral bone is removed.

Conclusions

Results obtained by FE methods and laboratory investigations suggest that keeping the subchondral bone to improve stress distribution, drilling three large anchorage holes, with chamfered necks and depth of the hole not exceeding diameter, perpendicularly to the floor of the acetabulum give better resistance to torque. This proposed fixation technique is a combination of the first (Charnley, 1979) and new generation (Malchau, Herbert, 1998) of cementing techniques. The proposed jigs and drill bit were designed to assist orthopaedic surgeons drill the desired geometry and distribution of anchorage holes perpendicularly to the acetabulum, thereby improving the long-term stability of the acetabular component in THR.

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