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A biomechanical study of the Birmingham Mid Head Resection arthroplasty: effect of stem size on femoral neck fracture

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Abstract

The Birmingham Mid Head Resection (BMHR) arthroplasty can be used as an alternative to conventional stemmed total hip arthroplasty in young patients unsuitable for hip resurfacing. This study investigated the effect of stem size on femoral neck fracture in the BMHR. Sawbones composite femurs were randomly allocated to one of the following groups: 1) Unprepared femur with no prosthesis; 2) Femur prepared with a Birmingham Hip Resurfacing prosthesis (BHR); 3) Femur prepared with a BMHR stem size 1 stem (BHMR-1); 4) Femur prepared with a BMHR stem size 3 stem (BHMR-3). Each femur was subjected to a compressive force using a materials testing machine until fracture of the femoral neck occurred. The highest force at fracture was in the unprepared femurs with a mean (\pm standard deviation) force at failure of 5.9 ± 0.2 kN. The mean force at failure for the femurs fitted with a prosthesis was 2.6 ± 0.4 kN, 3.0 ± 0.4 kN and 3.5 ± 0.5 kN, for the BHR, BMHR-1 and BMHR-3, respectively. Statistical analysis showed that the failure force for the unprepared femur was significantly ($p < 0.05$) greater than that of the BHR, BMHR-1 and BMHR-3. There was a significant difference ($p < 0.05$) between the force at failure for the BMHR-1 and BMHR-3, indicating that these two stem sizes have an effect on fracture force.

Keywords: Birmingham Mid Head Resection arthroplasty; Fracture; Hip; Mechanical Testing

Introduction

Hip resurfacing is an alternative to total hip replacement in young, active patients with end stage hip arthritis.¹⁻³ Despite recent controversies of some metal on metal hip arthroplasty^{4,5}, the literature contains excellent short and medium term results of the new generation of metal on metal hip resurfacing.¹⁻³ The advantages of preservation of proximal femoral bone stock, low dislocation risk and the excellent wear characteristics make hip resurfacing an attractive alternative to total hip replacement. However, hip resurfacing may not be the option for patients with poor bone quality as it can result in collapse, implant loosening and femoral neck fracture. Patients with abnormal proximal femoral anatomy (e.g. Perthe's disease) can also lead to sub-optimal placement of a hip resurfacing device and therefore lead to premature failure. For these groups of young active patients a new generation of prosthesis has been designed known as the Birmingham Mid Head Resection (BMHR) (Smith & Nephew Ltd, Warwick, UK). This prosthesis provides an alternative option to these patients who would otherwise require a conventional stemmed total hip arthroplasty.⁶⁻⁸

The BMHR consists of a short uncemented titanium alloy stem and a large cobalt chrome femoral head (Figure 1). The short stem provides the advantage of not violating as much of the femoral canal as conventional total hip replacement. This provides the advantage of preserving bone for future revision surgery. The device uses an osteotomy placed through the base of the femoral head which exploits the natural geometry of the femoral neck to provide a stable fixation for the internal cone of the implant.

One of the failure modes seen in hip resurfacing is fracture.⁹ The introduction of the BMHR may weaken femurs in a similar way to hip resurfacing. Therefore, the aim of this study was to investigate the effect of BMHR stem size on femoral neck fracture and to compare with the conventional Birmingham Hip Resurfacing (BHR) prosthesis.

Materials and methods

Materials

Forth generation Sawbones (Pacific research laboratories Inc, Vashon, WA, USA) composite femurs (item# 3406) were obtained. The femurs were randomly allocated to one of the following groups, with six specimens in each group:

1. Unprepared femur with no prosthesis.
2. Femur prepared with a diameter 48 mm Birmingham Hip Resurfacing prosthesis with the stem cemented (BHR);
3. Femur prepared with a diameter 48 mm Birmingham Mid Head Resection prosthesis with a size 1 stem (BMHR-1);
4. Femur prepared with a diameter 48 mm Birmingham Mid Head Resection prosthesis with a size 3 stem (BMHR-3).

All prostheses were provided by Smith & Nephew Ltd (Warwick, UK). The femurs fitted with a BHR/BHMR prosthesis were prepared following the manufacturers published surgical techniques.^{10,11} Briefly, the femurs were prepared by initially placing a guide wire in a neutral coronal alignment equal to the neck shaft angle of the synthetic femurs (120°). This guide wire provided the alignment of the central canal drill. The femurs were then prepared using standard instruments for a BHR/BMHR prosthesis (Smith & Nephew Ltd, Warwick, UK). For the BHR samples, a number of cement keyholes were drilled into the femoral head and bone cement (Surgical Simplex, Howmedica International, Limerick, Ireland) was used to fix the BHR specimens to the femurs. For the BHMR samples, a cementless stem was fitted into the femurs and then the prosthesis head was impacted into place.

Methods

An Instron TT-D materials testing machine (Instron, High Wycombe, UK) fitted with a 60 kN load cell was used to mechanically test each specimen. Specimens were fixed to the materials testing machine by upper and lower jigs. The lower jig comprised an aluminium cylinder which was attached to the base of the materials testing machine. The distal femur

was fixed to the cylinder by a series of screws. The upper jig was designed to contact the femoral/prosthesis head in order to apply a compressive load. The jig consisted of a block, with a spherical cavity of radius 27 mm that the femoral/prosthesis head located into. The block was manufactured from the polymer Fullcure 720 using an Eden 250 3D Printing System (Objet GmbH, Rheinmünster, Germany) and it was connected to the actuator of the materials testing machine using a metal frame. The test set-up is shown in Figure 2. The composite femurs were positioned in the upper and lower test jigs. The femur was aligned vertically in the sagittal plane with the femoral condyles in contact with the base of the lower jig to give a physiological position. The femoral head mated with the spherical cavity of the upper jig. Each specimen was placed relative to marks placed on the test jigs. The actuator of the materials testing machine was set to compress the femurs at a displacement rate of 0.17 mm/s. Load and displacement were recorded throughout the tests. Testing continued until failure occurred. Graphs of load against displacement were plotted, and the maximum load was determined. A third order polynomial was then fitted through the data. The polynomial was differentiated and the stiffness was determined at 2 mm; 2mm was chosen so that a comparison could be made for all femurs. The polynomial was then integrated to determine the energy absorbed just prior to fracture.

Statistical analysis was performed using SigmaPlot, version 11 (Systat Software Inc, Hounslow, London, UK). A Kruskal-Wallis one way analysis of variance (ANOVA) was undertaken using the Student-Newman-Keuls method for multiple comparisons to investigate significant differences between the four groups of femurs. Results were considered significant if $p < 0.05$.

Results

Figure 3 shows a typical example of a graph of force against displacement for one of the specimens. The forces to cause fracture of the unprepared femurs and femurs fitted with a BHR, BMHR-1 and BMHR-3 are shown in Table 1. The highest force at fracture was in the unprepared femurs with a mean (\pm standard deviation) force of 5.9 ± 0.2 kN. The mean force at failure for the femurs fitted with a prosthesis was 2.6 ± 0.4 kN, 3.0 ± 0.4 kN and 3.5 ± 0.5 kN, for the BHR, BMHR-1 and BMHR-3, respectively. It can be seen that the failure force increased from BHR to BMHR-1 to BMHR-3. Statistical analysis showed that the failure force for the unprepared femur was significantly ($p < 0.05$) greater than that of the BHR, BMHR-1 and BMHR-3. The failure force for the BMHR-3 was significantly ($p < 0.05$) greater than the BMHR-1 and BHR, while the BMHR-1 was significantly ($p < 0.05$) greater than the BHR.

The fracture patterns in the femurs varied (Figure 4). For the unprepared femurs, the crack initiated in the superior neck area and roughly followed the intertrochanteric line (Figure 4a). For the BHR, BMHR-1 and BMHR-3 there were two fracture patterns observed:

1. the crack initiated on the superior bone/implant interface and propagated towards the medial calcar (Figure 4b)
2. there was a transcervical vertical shear fracture at the implant/bone interface, followed by cracks into the inferior area of the neck (Figure 4c).

The stiffness of the femurs is shown in Table 2. It can be seen that the femur fitted with the BHR had the highest mean stiffness of 804.9 ± 105.9 N/mm and this was significantly greater ($p < 0.5$) than the unprepared femur, BMHR-1 and BMHR-3. No other significant difference were seen between the unprepared femur, BMHR-1 or BMHR-3.

The energy absorbed just prior to fracture is shown in Table 3, with the unprepared femur showing the highest value at 22.8 ± 2.0 J. The energy absorbed for the unprepared femur was significantly greater ($p < 0.5$) than the BHR, BMHR-1 and BMHR-3. The BMHR-1 and

BMHR-3 were both significantly greater ($p < 0.5$) than the BHR. There was no significant difference between the BMHR-1 and BMHR-3.

Discussion

This study provides biomechanical evidence that the introduction of the Birmingham Mid Head Resection (BMHR) arthroplasty significantly weakens the femur when compared to intact specimens and may predispose it to femoral neck fracture. Weakening of the femur with the introduction of the Birmingham Hip resurfacing (BHR) arthroplasty has been previously reported.¹² The use of the BMHR-1 and BMHR-3 prosthesis reduced the strength of the femur by 49% and 41%, respectively. The femur fitted with the BHR reduced the strength by 56%. There was a significant difference in the failure force between the femurs fitted with the BMHR-1 and BMHR-3 prostheses, indicating that the size of stem may affect the failure force.

The forces at failure for the BMHR-3 and BMHR-1 were significantly greater than the BHR. Olsen et al.¹³ found that the failure force for the BMHR (a mixture of BMHR-2 and BMHR-3) was significantly less than that of the BHR. However, there are major differences in the studies. Olsen et al.¹³ used cadaveric femurs that were cut 170 mm below the greater trochanter and potted using bone cement. The current study used composite femurs with fixation of the distal femur. The angle of prosthetic implantation may also lead to significant differences in the results of this study and that of Olsen et al.¹³ In their study the implant was positioned in 10 degrees of valgus compared to a neutral alignment in our study. Davis et al.¹² showed a significant increase in the load to failure when the BHR prosthesis was implanted in 10 degrees of valgus compared to a neutral alignment. However the study of Olsen et al.¹⁴ showed no significant increase in load to failure in implanting the BMHR in a valgus position compared to a neutral position. Davis et al.¹² showed approximately 40% increase in load to failure when positioning a BHR in 10 degrees of valgus compared to a neutral position in 3rd generation synthetic femurs with the same neck shaft angle and tested in a similar method to ours. If this 40% increase in load to failure is used to calculate the expected load to failure in this study the BHR load to failure just exceeds that of the BMHR size 3 stem construct. Therefore the sensitivity of the BHR device to varus/valgus positioning may explain the relative disparity between the finding of this study and that of

Olsen et al.¹³ The differences between these studies shows the need for a standardised method for testing and the need for further testing involving cadavers and Sawbones composite femurs.

The data showed that the femur fitted with the BHR had the highest mean stiffness. The femurs fitted with the BMHR-1 and BMHR-3 had stiffness values closer to the intact femur. This can be explained by the BMHR-1 and BMHR-3 having a much smaller stem and leaving more bone in place. Analysis of the energy absorbed just prior to fracture shows that fitting a femur with a BHR, BMHR-1 or BMHR-3 less energy to cause fracture compared to the intact femur.

The fracture patterns observed in this study are consistent with previous studies. For the unprepared femurs, the crack initiated in the superior neck area and roughly followed the intertrochanteric line (Figure 3a), was also seen by Davis et al..¹² The cracks seen in the femurs prepared with the BHR, BMHR-1 and BMHR-3 are consistent with previous studies.^{12,13}

One published clinical study on the BMHR shows that fracture of the proximal femur occurred in 2 out 156 hips (1.3%).⁷ Femoral neck fracture rates of around 1-2% for the BHR have been reported.^{15,16} Purely based on the mechanical testing in this study using composite femurs, a fracture rate for the BMHR would be expected to be similar or less than the BHR. However, as seen in the study by Olsen et al¹³ differences can be seen when cadaveric femurs are used and further investigation is required into the effect of stem size of the BMHR on fracture forces. These investigations will required a standardised method involving cadaveric and synthetic femurs, as well as a larger range of stem sizes.

We accept the limitation of this study are that a basic biomechanical model of the proximal femur was used which may not precisely replicate the behavior of bone in vivo. We accept that the findings in this study only represent failure with respect to femoral neck fracture

rather than cyclical loosening of the component. This is particularly relevant when considering the difference in fixation principles between the cemented BHR and the uncemented BMHR. The BHMR once ingrown may function very differently and therefore the finding of this study should only be considered in the early postoperative period. However this is the time when the majority of femoral neck fracture have been reported after hip resurfacing.⁹ The absence of hip joint muscle attachments in our mechanical testing construct and the use of only axial compression are a limitation. However, it has been reported that under normal gait loading the femur is primarily in a state of axial compression^{17,18} with previous literature supporting biomechanical testing conducted under this assumption.¹⁹ The use of static loading in single leg stance also limits the generalizations of these findings.

Conclusions

This study has used composite femurs to investigate the effect of stem size on femoral neck fracture in the Birmingham Mid Head Resection arthroplasty. The following conclusions were found:

- The highest force at fracture was in the unprepared femurs with a mean failure force of 5.9 kN;
- The mean failure force for the femurs fitted with a prosthesis was 2.6 kN, 3.0 kN and 3.5 kN, for the BHR (cementless stem), BMHR-1 (cemented stem) and BMHR-3 (cemented stem), respectively;
- Statistical analysis showed that the failure force for the unprepared femur was significantly ($p < 0.05$) greater than that of the BHR, BMHR-1 and BMHR-3;
- There was a significant ($p < 0.05$) difference between the force at failure for the BMHR-1 and BMHR-3, indicating that these two stem sizes have an effect on fracture force.

Conflict of interest statement

Mr Edward Davis has received financial remuneration for consultancy in providing educational services to Smith and Nephew Ltd. Funding for the project was provided by

Smith and Nephew Ltd, but they played no part in the design and execution of the experiments nor in the interpretation of the results.

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Table 1. Maximum force, mean and standard deviation for the femurs: unprepared, BHR, BMHR-1 and BMHR-3. An ANOVA power calculation has been undertaken using SigmaPlot, version 11 (Systat Software Inc, Hounslow, London, UK) with the power calculated to be 100%, indicating that six specimens were sufficient.

| Specimen | Unprepared (kN) | BHR (kN) | BMHR-1 (kN) | BMHR-3 (kN) |
|----------|-----------------|----------|-------------|-------------|
| 1 | 5.6 | 2.6 | 2.8 | 3.5 |
| 2 | 5.7 | 2.2 | 2.8 | 3.5 |
| 3 | 6.2 | 2.8 | 3.8 | 4.4 |
| 4 | 6.0 | 2.3 | 2.8 | 3.2 |
| 5 | 5.9 | 2.3 | 2.8 | 3.5 |
| 6 | 6.0 | 3.2 | 3.2 | 3.1 |
| Mean | 5.9 | 2.6 | 3.0 | 3.5 |
| SD | 0.2 | 0.4 | 0.4 | 0.5 |

Table 2. Stiffness, mean and standard deviation for the femurs: unprepared, BHR, BMHR-1 and BMHR-3.

| Specimen | Unprepared | | | |
|----------|------------|------------|---------------|---------------|
| | (N/mm) | BHR (N/mm) | BMHR-1 (N/mm) | BMHR-3 (N/mm) |
| 1 | 830.3 | 858.6 | 627.6 | 672.4 |
| 2 | 637.8 | 690.1 | 515.1 | 736.2 |
| 3 | 568.7 | 808.0 | 680.9 | 735.6 |
| 4 | 775.5 | 813.9 | 654.1 | 674.3 |
| 5 | 820.8 | 690.3 | 625.0 | 639.5 |
| 6 | 642.9 | 968.7 | 577.4 | 623.7 |
| Mean | 712.7 | 804.9 | 613.4 | 680.3 |
| SD | 110.2 | 105.9 | 59.2 | 47.2 |

Table 3. Energy absorbed just prior to fracture, mean and standard deviation for the femurs: unprepared, BHR, BMHR-1 and BMHR-3.

| Specimen | Unprepared (J) | BHR (J) | BMHR-1 (J) | BMHR-3 (J) |
|----------|----------------|---------|------------|------------|
| 1 | 20.4 | 4.2 | 12.0 | 11.6 |
| 2 | 24.6 | 3.5 | 14.4 | 17.1 |
| 3 | 25.3 | 5.3 | 11.7 | 16.0 |
| 4 | 21.2 | 4.9 | 7.8 | 8.7 |
| 5 | 21.6 | 3.8 | 5.6 | 11.6 |
| 6 | 23.9 | 4.8 | 7.1 | 7.5 |
| Mean | 22.8 | 4.4 | 9.8 | 12.1 |
| SD | 2.0 | 0.7 | 3.4 | 3.8 |

Figures



Figure 1. The Birmingham Mid Head Resection (BMHR) prosthesis. The short uncemented titanium alloy stem and a large cobalt chrome molybdenum alloy femoral head can be seen.



Figure 2. Test set up showing the distal femur secured to the aluminium cylinder by a series of screws. The load was applied to the femoral head by a fixture, which was attached to the actuator of the testing machine.

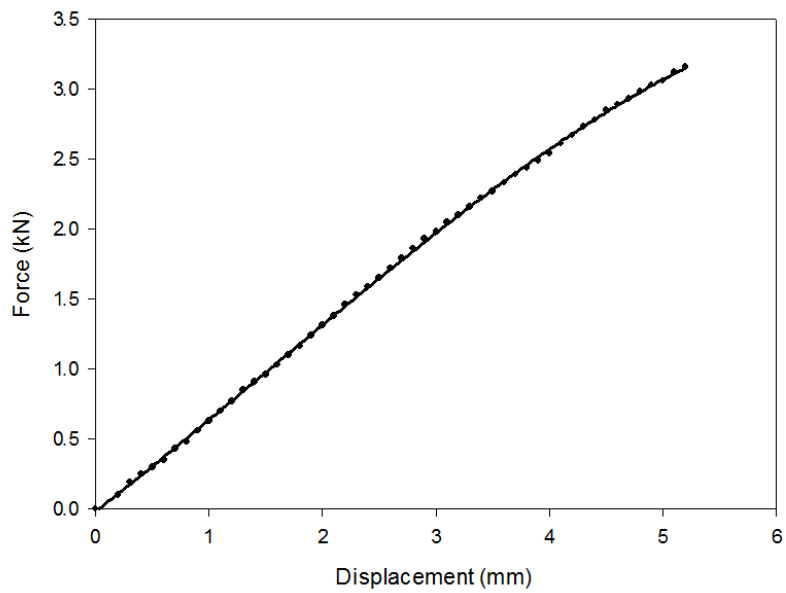


Figure 3. Force (F) plotted against displacement (d) for BMHR-3, specimen 4. The solid line represents a third order polynomial curve fit: $F = -0.008d^3 + 0.042d^2 + 0.603d$; $R^2 = 0.99$; $p < 0.0001$.





Figure 4. Fracture patterns seen in the femurs (a) crack initiated in the neck and roughly followed the intertrochanteric seen in the intact femurs; (b) crack initiated on the superior area of the neck and propagated towards the medial calcar seen in the femurs fitted with a BHR, BMHR-1 or BMHR-3; figure is for the BMHR-1; (c) cracks confined to the inferior area of the neck seen in the femurs fitted with a BHR, BMHR-1 or BMHR-3; figure is for the BMHR-3.