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Abstract: The aim is to compare the strain pattern in intact and resurfaced femurs using validated third-generation composite femurs and rosette strain gauges. The rosette strain gauges were applied to an intact and a resurfaced third-generation composite femur at three sites: the narrowest part of the lateral surface of the neck, the narrowest part of the medial surface of the neck, and the medial surface at the level of the lesser trochanter. The maximum and minimum principal strains were calculated at axial loads of 600, 800, and 1000 N. Further tests were carried out with an additional abductor load. The maximum principal strains in the resurfaced femur were approximately 50 per cent higher in the lateral surface of the neck and about 25 per cent higher in the lesser trochanteric region than in the intact femur. Inclusion of the abductor force decreased the strains in both the intact and the resurfaced femurs, particularly at the lateral surface of the femoral neck. Increased strain at the lateral surface of the femoral neck following hip resurfacing could be a cause of neck fracture, particularly if there are other predisposing factors such as notching of the femoral neck and/or abductor dysfunction. Meticulous repair of the abductors is warranted if a lateral approach is used.

Keywords: surface replacement, hip, strain pattern

1 INTRODUCTION

Surface replacement arthroplasty of the hip using a metal-on-metal bearing is an increasingly popular option in the treatment of young active patients with hip arthritis. Contemporary hip resurfacing is an attractive concept as it reduces the risk of wear particle-induced osteolysis and it preserves the bone stock of the proximal femur should revision surgery be required. The large diameter of the articulation also offers increased stability and enhanced range of movement compared to ‘conventional’ total hip replacement (THR). It has been suggested that the load transfer in the proximal femur after a resurfacing procedure is similar to the normal hip, so reducing the risk of stress shielding. However, fracture of the femoral neck is a well-documented early complication of hip resurfacing, with an incidence of 1–2 per cent [**1**, **2**].

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Unlike conventional total hip replacement, there is a paucity of published biomechanical studies on surface replacement arthroplasty. The purpose of this study was to compare the strain pattern in a resurfaced femur with that in an intact femur and to determine the influence of the abductor force on the strain pattern.

2 MATERIAL AND METHODS

Two validated third-generation composite femurs [**3**] were used for the tests (model 3306, Sawbones, Pacific Research Laboratories, Inc., Vashon, Washington). One of the femurs was prepared by the senior author to accept an appropriate-sized Durom™ resurfacing femoral component (Zimmer, Warsaw, US) using the standard instruments. The femoral component was placed neutral to the neck-shaft angle of the composite femur ($\sim 135^\circ$). The femoral component was cemented with Simplex™ P bone cement (Stryker, Berkshire, UK). Based on the recommendations in the manufacturers’ operative technique manual, the stem of the implant was not cemented. The stem of the Durom femoral component is designed for alignment and not force transmission.

Both the intact and resurfaced femurs were fixed in separate pots with rapid setting cement (Supamix Ltd, Griff Lane, Warwickshire UK). The femurs were positioned at 10° valgus angulation in the coronal plane to simulate physiological inclination during the single-leg stance [**4**]. In the sagittal plane the femurs were positioned at 0°. After potting, the femurs were left undisturbed for a minimum of 24 h.

The function of the hip abductor muscles was simulated by a broad nylon strap which was fixed to the abductor insertion on the greater trochanter by multiple screws and directed at 20° to the vertical. Rosette strain gauges (FRA-2-11, Tokyo Sokki Kenkyujo Co. Ltd, Japan) were applied at three identical sites in each femur: site 1, narrowest part of the lateral surface of the neck; site 2, narrowest part of the medial surface of the neck; and site 3, medial surface at the level of lesser trochanter. Each rosette strain gauge was made up of three strain gauges mounted at 45° angles to each other. The middle gauge (third axis) was always positioned along the longitudinal axis of the femur so that the first axis was anterior to it and the second axis was posterior to it (Fig. 1).

The sites of application of the strain gauges were prepared with sandpaper. The strain gauges were bonded to the femoral surfaces at the above sites by means of a cyanoacrylate adhesive. The leads of the strain gauges were soldered to terminals fixed to the femur immediately adjacent to the strain gauges. The strain gauges were connected to a strain gauge amplifier (model SGA870, CIL Electronics Ltd, Worthing, with a CIL Electronics switchbox). The strain gauges were checked for electrical continuity and for internal resistance (120 Ω). Adequacy of insulation of all the electrical terminals was checked.

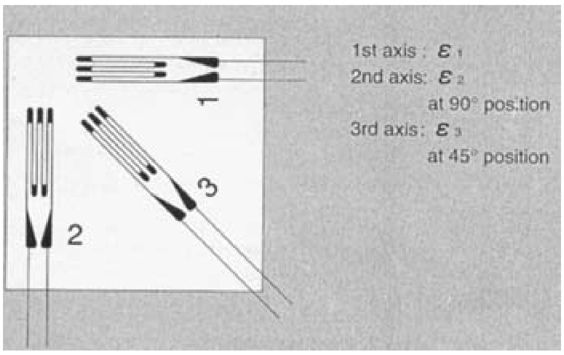

Fig. 1 Rosette strain gauge showing the relative angle of the individual components

For each strain gauge the corresponding strain gauge from the other unloaded femur was used as a dummy (to compensate for thermal expansion or contraction), so that the strain gauges were connected in a half-bridge configuration. The voltage reading from the strain gauge amplifier was multiplied by a conversion factor of 400. This gave the strain measurement in microstrains (με).

Preliminary testing was done using a load of 600 N to preload the femurs and to test the creep response. An appropriate-sized Durom acetabular cup was placed over the femoral head and the vertical load was applied using a Testometric M500K universal testing machine (5 mm/min). There was a decrease in the applied load with time due to the creep in the femur. Consequently, it was necessary to adjust the load so that a constant load of 600 N could be maintained. The unloaded femurs were allowed to recover overnight before the definitive testing was commenced.

1. *Strain measurement without including an abductor force*. The femurs were tested sequentially. Each was loaded at a rate of 5 mm/min to reach 600 N. The load was continuously maintained at 600 N for 3 min to compensate for the creep phenomenon (the 3 min loading time was chosen as there was not further change in the strain during preliminary testing). At this point the strain measurements were recorded. Further strain measurements were measured in a similar manner at 800 and 1000 N without removing the femur from the jig. The femur within the pot was then removed and repositioned in the testing machine. The sequence was repeated twice to give a total of three repetitions.

   The strain gauge amplifier was not recalibrated to zero between the repetitions. Consequently, the strain readings in the first test were likely to be lower than the readings in the second test, which in turn were likely to be lower than the readings in the third test because of the creep phenomenon.
2. *Strain measurement with inclusion of an abductor force*. In the second part of the study both the femurs were sequentially loaded with an additional abductor force. The abductor mechanism was simulated by applying traction to the nylon strap through a pulley and weight system. Testing was done with an axial load of 600 N and with an abductor force of 400 N. This test was repeated three times. The test rig was dismantled between each test, but the strain gauge amplifier was not recalibrated to zero between the repetitions.

3. *Calculation*. The maximum and minimum principal strains in each rosette gauge were calculated as follows [**5**]

   Maximum principal strain (ε max)

$$=\tfrac{1}{2}\{\varepsilon_1+\varepsilon_2+\sqrt{2[(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2]}\}$$

   Minimum principal strain (ε min)

$$=\tfrac{1}{2}\{\varepsilon_1+\varepsilon_2-\sqrt{2[(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2]}\}$$

   where ε_1 is the strain from the anterior strain gauge (axis 1), ε_2 is the strain from the posterior strain gauge (axis 2), and ε_3 is the strain from the middle strain gauge (axis 3).

   The maximum principal strain (ε max) at the lateral surface (site 1) gives the maximum tensile strain (positive value). The minimum principal strains (ε min) at the medial surface (sites 2 and 3) give the maximum compressive strains at those two sites respectively (negative value). For each site the strains at the same load and the same test repetition were compared between the unoperated and the resurfaced femur.

3 RESULTS

1. *Comparison of strain without the abductor force.* The tensile strain at the lateral surface of the femoral neck (site 1) consistently remained approximately 50 per cent higher in the resurfaced femur when compared with the intact femur (Table 1). The difference in the strain increased from about 40 per cent at 600 N to about 60 per cent at 1000 N. This increase was seen in all the three repetitions of the test. In contrast, the compressive strain at the medial surface of the femoral neck (site 2) was almost equal in both the resurfaced femur and the intact femur at all loads and in all the three repetitions. However, the compressive strain at the medial surface of the femur at the level of the lesser trochanter (site 3) consistently remained approximately 25 per cent higher in the resurfaced femur.
2. *Comparison of strain with abductor force included.* With the addition of the abductor force, the tensile strain at the lateral surface of the femoral neck decreased by about 25 per cent in the

Table 1 Comparison of strain between the intact and resurfaced femurs without inclusion of the abductor force

Axial load (N)	Site	Test repetition	Strain in the intact femur without abductor force (με)	Strain in the resurfaced femur without abductor force (με)	Strain in the resurfaced femur expressed as percentage of strain in the intact femur (%)
600	1	First	375	556	148
		Second	439	592	135
		Third	457	631	138
	2	First	−436	−451	103
		Second	−473	−478	101
		Third	−499	−490	98
	3	First	−335	−443	132
		Second	−363	−453	124
		Third	−386	−473	122
800	1	First	505	790	156
		Second	547	821	150
		Third	580	861	148
	2	First	−616	−605	98
		Second	−642	−622	97
		Third	−664	−643	98
	3	First	−475	−606	128
		Second	−497	−622	125
		Third	−518	−648	125
1000	1	First	638	1046	164
		Second	669	1067	159
		Third	717	1097	153
	2	First	−768	−752	98
		Second	−803	−773	96
		Third	−841	−791	94
	3	First	−598	−781	131
		Second	−627	−782	125
		Third	−657	−825	126

resurfaced femur when compared to the strain without the abductor force (Table 2). The compressive strain at the medial surface decreased by approximately 15 per cent under the influence of the abductor force. Addition of the abductor force also decreased the absolute strain in the intact femur (Table 3).

Despite the absolute decrease in the strain, the tensile strain at the lateral surface of the neck remained 51–94 per cent higher in the resurfaced femur when compared with the intact femur in the presence of the abductor force (Table 4). The compressive strain at the medial surface of the neck was 4–25 per cent higher in the resurfaced femur, whereas the compressive strain at the medial surface of the femur at the level of the lesser trochanter was about 21 per cent higher in the resurfaced femur. It was noted that the difference between the femurs in the first test was higher than in the other two repetitions, but the reason for this is not known. The tensile strain at the lateral surface of the femoral neck in the resurfaced femur without the abductor force (*worst-case scenario*) was more than twice the

Table 2 Comparison of strain in the resurfaced femur with and without inclusion of the abductor force

Load (N)	Site	Test repetition	Strain in the resurfaced femur with abductor force (με)	Strain in the resurfaced femur without abductor force (με)	Strain with abductor force expressed as percentage of the strain without abductor force (%)
600	1	First	465	556	84
		Second	476	592	80
		Third	481	631	76
	2	First	−385	−451	85
		Second	−392	−478	82
		Third	−393	−490	80
	3	First	−396	−443	89
		Second	−399	−453	88
		Third	−406	−473	86

Table 3 Comparison of strain in the intact femur with and without inclusion of the abductor force

Load (N)	Site	Test repetition	Strain in the intact femur with abductor force (με)	Strain in the intact femur without abductor force (με)	Strain with abductor force expressed as percentage of the strain without abductor force (%)
600	1	First	239	375	64
		Second	284	439	65
		Third	318	457	70
	2	First	−308	−436	71
		Second	−359	−473	76
		Third	−376	−499	75
	3	First	−326	−335	97
		Second	−327	−363	90
		Third	−335	−386	87

Table 4 Comparison of strain between the intact and resurfaced femurs with inclusion of the abductor force

Load (N)	Site	Test repetition	Strain in the intact femur with abductor force (με)	Strain in the resurfaced femur with abductor force (με)	Strain in the resurfaced femur expressed as percentage of strain in the intact femur (%)
600	1	First	239	465	194
		Second	284	476	167
		Third	318	481	151
	2	First	−308	−385	125
		Second	−359	−391	109
		Third	−376	−393	104
	3	First	−326	−396	121
		Second	−327	−399	122
		Third	−335	−406	121

Table 5 Comparison of strain between the intact femur with inclusion of the abductor force and the resurfaced femur without the abductor force

Load (N)	Site	Test repetition	Strain in the intact femur with abductor force (με)	Strain in the resurfaced femur without abductor force (με)	Strain in the resurfaced femur without abductor force expressed as percentage of strain in the intact femur with abductor force (%)
600	1	First	239	556	232
		Second	284	596	208
		Third	318	631	198
	2	First	−308	−451	146
		Second	−359	−478	133
		Third	−376	−490	130
	3	First	−326	−443	135
		Second	−327	−453	138
		Third	−335	−473	141

tensile strain in the intact femur with the abductor load (*best-case scenario*) (Table 5).

5 DISCUSSION

Stress-shielding underneath the resurfacing femoral component has been reported in experimental studies [**6–8**]. High strains have been found at the rim of the femoral component by experimental studies [**9**] and finite element analysis [**8**]. Blatcher used quantitative holographic inferometry and found that the tensile strains in the femoral neck were 60 per cent higher following resurfacing arthroplasty [**10**].

Taylor [**11**], in a very recent finite element analysis study, also found that resurfacing increased strain in the superior femoral neck. Although the increase in the femoral neck strain was significant, the mean strains were below the yield strain for cancellous bone. Peak strains were observed above the yield strain, but they accounted for less than 1 per cent of the total head–neck bone volume. The present study using strain gauges also demonstrates that the strain in the lateral surface of the neck is approximately 50 per cent higher following surface replacement arthroplasty when compared with an intact femur.

It was found that when the abductor force was included, the absolute strain was found to be less than the strain without the abductor force, although the strain in the resurfaced femur still remained relatively high compared to the intact femur. Frankel and Pugh [**12**] predicted that the neutralizing effect of the abductor force on the bending moment would enable the femoral neck to sustain higher loads than would otherwise be possible. Other theoretical models have also supported this view [**13–16**]. A more recent finite element analysis has suggested that inclusion of ligamentous and muscular forces has the effect of generating compressive stresses across most of the proximal femur [**17**].

Capello *et al.* [**18**], on analysing the failures following early surface replacement arthroplasty, noted that an abductor lurch, indicating abductor muscle dysfunction, was present in 50 per cent of the patients who subsequently sustained femoral neck fractures. In their series the hip was approached by either a transtrochanteric or a lateral approach (reflecting the abductors).

In this study, third-generation composite femurs have been used to decrease interspecimen variation. Only two femurs were used which is a potential weakness of the study. However, a previous validation study has found an interspecimen variability of only between 2.6 and 3.1 per cent for the axial and bending load [**3**]. Although the material properties of the composite femurs have been validated, it may not represent the *in vivo* situation with regard to the absolute strain and cement penetration properties. The abductor model used in the present study is a very simplified model. It is possible *in vivo* that the actions of the other muscles around the hip and the effects of the ligamentous constraints of the hip joint could also affect the strain pattern in the proximal femur.

5 CONCLUSION

Even with the above limitations, this study indicates that the tensile strain at the lateral surface of the femoral neck is increased following a surface replacement arthroplasty when compared with an intact femur. There would be risk of femoral neck fracture, particularly if there were other predisposing factors such as notching of the femoral neck. If the procedure is done using the lateral approach (reflecting the abductor muscles), careful repair is required to avoid abductor dysfunction. Further larger studies using a more physiological model or *in vivo* measurements following surface replacement arthroplasty are likely to give more accurate insights into the biomechanics following surface replacement arthroplasty.

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