Is a valgus position of the femoral component in hip resurfacing protective against spontaneous fracture of the femoral neck?

A BIOMECHANICAL STUDY

C. Schnurr,
J. Nessler,
C. Meyer,
H. H. Schild,
J. Koebke,
D. P. König

*From the Rheinische
Klinik für
Orthopädie, Viersen,
Germany*

The aim of our study was to investigate whether placing of the femoral component of a hip resurfacing in valgus protected against spontaneous fracture of the femoral neck.

We performed a hip resurfacing in 20 pairs of embalmed femora. The femoral component was implanted at the natural neck-shaft angle in the left femur and with a 10° valgus angle on the right. The bone mineral density of each femur was measured and CT was performed. Each femur was evaluated in a materials testing machine using increasing cyclical loads.

In specimens with good bone quality, the 10° valgus placement of the femoral component had a protective effect against fractures of the femoral neck. An adverse effect was detected in osteoporotic specimens.

When resurfacing the hip a valgus position of the femoral component should be achieved in order to prevent fracture of the femoral neck. Patient selection remains absolutely imperative. In borderline cases, measurement of bone mineral density may be indicated.

A major advantage of hip resurfacing is that it preserves bone stock in the proximal femur for later revision.¹⁻³ Other suggested benefits include better stability of the joint and proprioception and a reduced risk of leg-length discrepancy.^{2,4,5} Although excellent short- and medium-term results are available, there are as yet no long-term survival data.^{3,6-9} Modern metal-on-metal bearings have eliminated loosening caused by polyethylene wear debris, but other problems persist.¹⁰ Fracture of the femoral neck remains the most common complication of hip resurfacing^{3,9,11} with an incidence of between 0% and 2.8%.^{1,11-17} A review of 3497 surface replacements of the hip showed a rate of fracture of 1.91% for women and of 0.98% for men.¹⁷ Most of these occurred spontaneously within four months of surgery^{10,16-18} rather than as the result of trauma.^{13,15,17,19-22} It has been suggested that these early failures are less influenced by the design of the implant than by patient selection and operative technique.¹⁶

It can be difficult to select the most appropriate patient for resurfacing. Certainly, good bone density and an adequate body mass index and bone geometry are necessary.²³ The surgical procedure is challenging, and the impact of the cementing technique and the

final positioning of the implant is, although critical, not yet fully understood.

It has been shown that the orientation of the femoral component strongly influences the risk of fracture of the femoral neck.^{17,19,24-26} Common sense dictates that a varus placement will give a poor result and should be avoided,^{24,27} but the best position remains uncertain. In one study it was placed in maximum valgus,²⁸ while in others a fixed centre column diaphysis (CCD) angle of 140° was chosen.¹⁹ Some defined the target CCD angle as any valgus position compared with the pre-operative CCD angle.^{20,22,26} The reason for this seemingly random target position was based on a small number of biomechanical studies dealing with the implant-shaft angle.²⁹

No study has simulated spontaneous fracture of the femoral neck after hip resurfacing. It is therefore unclear whether valgus placement of the femoral component protects against fractures of the femoral neck.

We have examined the response of surface replacement to cyclical stress and to everyday occurrences, such as stumbling, to determine whether a valgus placement of the femoral component protected against spontaneous fracture of the femoral neck.

■ C. Schnurr, MD, Orthopaedic Surgeon
■ J. Nessler, Orthopaedic Surgeon
■ D. P. König, MD, Professor Rheinische Klinik für Orthopädie, Horionstrasse 2, 41749 Viersen, Germany.

■ C. Meyer, MD, Radiologist
■ H. H. Schild, MD, Professor Department of Radiology University of Bonn, Sigmund-Freudstrasse 25, 53105 Bonn, Germany.

■ J. Koebke, MD, Professor Department of Anatomy University of Cologne, Joseph-Stelzmannstrasse 9, 50931 Köln, Germany.

Correspondence should be sent to Dr C. Schnurr; e-mail: christophschnurr@gmx.de

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Table I. Details of the characteristics of the 15 specimens

Specimen number	Age (yrs)	Gender	Storage time (wks)	Implant size (mm)	T-score		
					Left	Right	Difference between left and right
1	67	M	60.0	49	-1.87	-1.47	0.40
2	66	M	53.7	51	-0.65	-0.72	0.07
3	50	M	42.7	47	-1.79	-1.60	0.19
4	69	M	43.4	49	0.19	0.00	0.19
5	78	M	71.0	46	-1.01	-1.08	0.07
6	79	W	74.0	47	-2.95	-3.02	0.07
7	63	M	47.0	51	1.80	1.41	0.39
8	80	M	58.0	49	-2.61	-2.54	0.07
9	82	W	70.7	43	-2.17	-1.95	0.22
10	72	W	66.0	39	-1.34	-1.10	0.24
12	68	M	40.0	53	-0.43	-0.84	0.41
13	86	M	51.0	47	-4.20	-3.68	0.52
14	75	M	64.7	51	-2.81	-2.59	0.22
18	78	M	44.7	49	-2.59	-2.51	0.08
19	70	W	56.7	46	-2.87	-2.99	0.12
Mean	72		56.2	48	-1.69	-1.65	0.22
SD	9		11.1	4	1.50	1.32	0.22
Range							
Minimum	50		40	39	-4.20	-3.02	0.07
Maximum	86		74	53	1.80	1.41	0.52

Materials and Methods

A total of 20 pairs of formalin embalmed human femora were obtained from the Department of Anatomy of the University of Cologne. Their mean storage time was 56.2 weeks (40 to 74, Table I). We excluded those with previous surgery of the hip or leg, known cancer, systemic disease affecting bone metabolism and infection.

The mean age of the cadavers from which the femora had been harvested was 71 years (50 to 86). There were 14 men and six women. One specimen pair (specimen 17) was excluded because of cancer of the femoral shaft. Another was rejected because of a large cyst in the femoral head (specimen 15) and one was fractured during milling (specimen 11). Two pairs were used to establish the biomechanical procedures (specimens 16 and 20). The remaining 15 pairs were used for biomechanical testing.

First CT. We obtained CT scans (Philips Mx8000 IDT16, Eindhoven, The Netherlands) of each pair of femora and reconstructed them in three dimensions. Because the projected and real CCD angles differed, anteversion of the femoral neck was measured and the femora were virtually rotated to allow measurement to be made parallel to the femoral neck. The CCD angle was measured between the anatomical axis of the femoral shaft and a line joining the centre of rotation of the hip to the mid-point of the smallest diameter of the femoral neck.

Measurement of bone mineral density (BMD). Each specimen was tested using dual-energy x-ray absorptiometry (DXA; Hologic QDR-2000, Bedford, Massachusetts). The BMD of the femoral neck was measured and the T-score

calculated. Any difference between the paired femora was identified. The specimens were then divided into those with a normal BMD ($T \geq -2.5$) and those which were osteoporotic ($T < -2.5$).

Operative technique. All implantations were performed by the senior authors (CS, JN) each of whom implanted half the total number of prostheses using computer navigation (Ci-Hip essentials 2.0.1; DePuy, Leeds, United Kingdom). In order to establish co-ordinates on the femur for real-time tracking during the procedure, a 5 mm pin was placed in the distal femur to which the optical unit was attached. The medial and lateral epicondyles, the lateral mid-neck point and the intended cap edge were registered using the navigation pointer as were point clusters on the femoral head and the superior, inferior, ventral and dorsal aspects of the femoral neck. The model automatically generated by the computer navigation device system was checked for accuracy. Thereafter, the target position of the femoral implant was adjusted by the surgeon. The left-sided prostheses were adjusted in the direction of the natural CCD angle and anteversion of the femur. The right-sided prostheses were placed in 10° of valgus which reflected the natural CCD angle and anteversion. The smallest possible femoral component was chosen for each pair of femora and both sides received the same size of implant.

A 2.4 mm guide wire was inserted into the femoral head and neck using a navigated drill guide. Navigated depth drilling was performed, after which the femoral head was prepared using the standard instrumentation. The stem was overreamed to prevent load transfer through it. High-viscosity

Fig. 1

Photograph showing the experimental set-up. The femur was placed in a position of 10° of valgus in the hydraulic testing machine and cyclical loads were applied vertically. The load cell was installed above the specimen.

cement (Smartset; DePuy) was finger-packed on to the reamed head and manually pressed into the trabecular bone after which the implant (ASR; DePuy) was inserted. If the planned implantation depth was not reached manually, the femoral component was carefully impacted with a 50 g hammer in an attempt to avoid microfractures. Each femoral head was photographed before and after implantation of the prosthesis.

Second CT. CT scans of each specimen were taken again and three-dimensional reconstructions obtained. The anteversion of the implant was measured and the virtual model again rotated to correct the discrepancy between it and the specimen. The real implant-shaft angle and femoral offset were measured in the coronal plane parallel to the femoral component.

Biomechanical testing. In the early period after hip resurfacing, most patients walk exerting only minimal or partial stress on the operated leg. In order to imitate the gradual increase in stress which occurs throughout the recovery period, these experiments exerted increasing cyclical loads. Biomechanical evidence has suggested that, during stumbling, the forces across the hip peak at roughly nine times the body-weight.³⁰ A standard body-weight of 70 kg (approximately 700 N) was assumed and a reasonable upper force limit of 6300 N (9×700 N) applied. Since the periods of increasing and decreasing force only last approximately 0.5 seconds *in vivo*,³⁰ a

sinusoidal frequency of 2 Hz was used. All specimens were tested in a hydraulic materials testing machine (MTS model 505-07; Eden Prairie, Minnesota; Software Flextest 2.3m, MTS) with a 10 kN load cell (type U2B; Hottinger HBM Messtechnik, Darmstadt, Germany). In accordance with the standard for testing total hip prostheses (ISO 7206-4)³¹ each specimen was transected distally at an angle of 10° to the anatomical axis of the shaft using the intramedullary instrumentation from a total knee replacement. Compression was applied vertically (Fig. 1). Each specimen was tested using an identical study protocol. Cyclical testing started with 700 N for 2000 cycles. Thereafter, the compressive load was increased incrementally (1400 N/2000 cycles; 2100 N/2000 cycles; 2800 N/2000 cycles; 3500 N/2000 cycles; 4200 N/2000 cycles; 4900 N/2000 cycles; 5600 N/2000 cycles; 6300 N/50 000 cycles). Throughout the test, force and displacement were continuously recorded. The fractures were recorded on video. Testing ceased if a fracture occurred. All the data were stored by the computer for later analysis. After fracture, each specimen was photographed and the fracture pattern, as classified by Morlock et al,¹⁶ identified.

Statistical analysis. No power analysis was performed. The Wilcoxon signed ranks test for related samples and the Mann-Whitney U test for independent samples were carried out to determine significance ($p = 0.05$). Correlations were evaluated using Pearson's correlation coefficient with significance set at $p = 0.05$. The software SPSS version 16.0 for Windows (SPSS Inc., Chicago, Illinois) was used for statistical analysis.

Results

BMD. Six pairs of femora were osteoporotic with a T-score below -2.5. There was no significant difference in the BMD between the right and left side for each pair (Wilcoxon signed ranks test, $p = 0.244$). A summary of the characteristics of each specimen pair is shown in Table I.

Operative procedure and second CT. In each case implantation was achieved without notching the femoral neck or leaving reamed cancellous bone uncovered by the femoral component. CT scans verified the natural CCD angle and the final position of the implant (Table II). In one pair (specimen 7) navigated implantation resulted in valgus malpositioning of both prostheses. The mean natural difference between the pre-operative CCD angle and the post-operative implant-shaft angle in the left-sided specimens was 0° of valgus (1° varus to 3° valgus). The mean difference for the right-sided specimens was 10° of valgus (SD 3). The mean difference between the sides of each pair was 11° (8° to 13°). Valgus placement reduced the femoral offset by a mean of 2.2 mm (-7.4 to 3.1, $p = 0.03$) when compared with the neutral side.

Biomechanical testing. Every femoral neck fractured during cyclical testing. The number of cycles to failure and the stress applied correlated with the BMD (Pearson's correlation coefficient 0.807, $p < 0.01$). A significant difference

Table II. Details of the first and second CT scans

Specimen number	CCD* angle (°)		Implant-shaft angle (°)		Difference between CCD and implant-shaft angles (°)		Difference between right and left implant-shaft angles (°)	Implant offset (mm)		Difference between right and left offset (mm)
	Left	Right	Left	Right	Left	Right		Left	Right	
1	125	125	125	134	0	9	9	36.9	33.6	-3.3
2	119	120	122	132	3	12	10	48.2	45.9	-2.3
3	122	122	125	137	3	15	12	43.0	38.5	-4.5
4	125	132	124	138	-1	6	14	34.9	35.2	0.3
5	125	122	124	136	-1	14	12	44.6	37.2	-7.4
6	129	133	131	141	2	8	10	36.0	35.1	-0.9
7 [†]	126	128	139	152	13	24	13	36.0	29.9	-6.1
8	129	132	129	138	0	6	9	29.9	32.6	2.7
9	124	125	126	134	2	9	8	38.8	41.9	3.1
10	119	122	119	131	0	9	12	27.3	25.1	-2.2
12	123	124	121	133	-2	9	12	53.0	49.4	-3.6
13	127	125	126	139	-1	14	13	45.9	39.3	-6.6
14	119	120	118	128	-1	8	10	50.5	46.2	-4.3
18	122	122	122	132	0	10	10	45.9	44.1	-1.8
19	128	131	129	141	1	10	12	33.3	33.5	0.2
Mean	124	126	124	135	0	10	11	40.6	38.4	-2.2
SD	6	3	5	4	2	3	2	7.9	6.6	3.1
Range										
Minimum	119	120	118	128	-1	6	8	27.3	25.1	-7.4
Maximum	129	133	131	141	3	14	13	53.0	49.4	3.1

* CCD, centre column diaphysis

† specimen 7 had been implanted in a valgus malposition and was not included in calculations of the mean, SD and range

was apparent between osteoporotic and non-osteoporotic bones (mean cycles to fracture for 10° of valgus; 4460 cycles (1 to 9638) with osteoporosis, 13 518 cycles (9605 to 19 206) without osteoporosis, $p = 0.003$; Table III). There was no correlation between the number of cycles to fracture (Mann-Whitney U test, $p = 0.003$) and the storage time of the embalmed femora (Pearson's correlation coefficient - 0.261, $p = 0.180$), size of implant (Pearson's correlation coefficient 0.003, $p = 0.986$) and the lateral femoral offset (Pearson's correlation coefficient = 0.117, $p = 0.553$).

For all specimens of normal BMD, valgus placement resulted in a higher resistance to cyclical stress. The mean number of cycles to fracture increased from 12 086 cycles (9453 to 16 995), with the femoral component in a neutral position, to 13 517 cycles (9605 to 19 206) in a valgus position (Wilcoxon signed ranks test, $p = 0.012$, Fig. 2). The pattern of these fractures was described as 'edge-to-out' (Fig. 3). The specimen with valgus malpositioning (specimen 7) was highly resistant to repetitive stress. The left femur in 13° of valgus fractured after 27 051 cycles and the right in 24° of valgus, after 69 070 cycles.

Specimens with low BMD and valgus placement of the femoral component were less resistant to fracture of the neck. The number of cycles to fracture decreased from 6784 with a neutral femoral component to 4460 for those in valgus (Wilcoxon signed ranks test, $p = 0.043$, Fig. 4). Only one (specimen 6) was an 'edge-to-out' fracture. The others were classified as 'edge-to-edge' (Fig. 3).

A summary of the material testing data is given in Table III.

Discussion

Fracture of the femoral neck is the most common complication of hip resurfacing.^{3,9} It is essential to understand why it occurs given its reported incidence of up to 2.8%.^{1,11-14,16,17,32} Previous studies have found differences in the pattern of fracture depending on the time interval between surgery and fracture, distinguishing between early failure which occurs within four months of surgery, and late failure.¹⁶ Late fractures were shown to have two phases.^{3,10,16} It was thought that excessive trauma at the time of implantation might cause microfracture within the head of the femur. After initial healing, a pseudarthrosis could develop and lead to a gradual loosening of the component rather than a sudden fracture.¹⁰

Our study has concentrated on fractures of the femoral neck which occur in the first four months after surgery. It is likely to depend on factors related to patient selection, biomechanics and surgical technique.³

The most critical step of the operation is likely to be the siting of the femoral component. Clinical studies have shown that a low implant-shaft angle is associated with a poor outcome.²⁴ A large Australian study which reviewed fracture of the femoral neck after hip resurfacing, found that the femoral component had been implanted in varus in 71% of the fractures.¹⁷ None had been implanted in valgus.

Table III. Details of the number of cycles required for fracture of the femoral neck

	Fracture cycles		
Specimen number	Left (neutral)	Right (10° of valgus)	Difference
Without osteoporosis			
1	12348	13242	894
2	11965	15368	3403
3	12077	12087	10
4	16995	19206	2211
5	11500	11659	159
7*	27051	69070	
9	9453	9605	152
10	10014	13322	3308
12	12334	13649	1315
Mean	12086	13518	1432
SD	2262	2847	1394
Range			
Minimum	9453	9605	10
Maximum	16995	19206	3308
With osteoporosis			
6	11069	9335	-1734
8	7210	4402	-2808
13	2024	1	-2023
14	1	1	0
18	12297	9638	-2659
19	8105	3382	-4723
Mean	6784	4460	-2325
SD	4886	4278	1545
Range			
Minimum	1	1	0
Maximum	12297	9638	-4723

* specimen 7 was implanted in a valgus malposition and therefore not included in the statistical analysis

Fig. 2a

Fig. 2b

Figure 2a – Graph showing that for all specimens with a normal bone mineral density valgus placement gave a higher resistance against fracture of the femoral neck. Figure 2b – Bar chart showing that the mean fracture cycles increased from 12 086 (neutral position) to 13 517 for the 10° valgus position (Wilcoxon signed ranks test $p = 0.012$). Whiskers indicate SD and the asterisk indicates a significance < 0.05 .

The high incidence of fracture is probably related to a doubling of the tensile stress across the upper part of the neck of the femur after resurfacing.²⁹ Two finite-element studies have shown that placing the femoral component in valgus reduces the peak stress at this point.^{25,26} Despite this, there are no consistent suggestions as to the optimal implant-shaft angle because there have been few biomechanical studies.^{19,20,26,28,29}

Analysis of recently published studies, suggests that most fractures occur spontaneously rather than as a result of trauma.^{5,12,13,15,21,22} A total of 21 of 50 fractures (42%) in the series were atraumatic.¹⁷

To the best of our knowledge there have been no biomechanical studies of spontaneous fractures of the neck of the femur after hip resurfacing to date.

We have shown that placing the femoral component in 10° of valgus protects the femoral neck from cyclical stresses in patients with good BMD. That they all failed with an 'edge-to-out' fracture pattern suggests that the biomechanical

event is reproducible and can simulate the type of neck fracture which occurs within a few weeks of surgery.¹⁶

Surprisingly, in specimens with poor BMD placing the femoral component in valgus reduced the resistance to cyclical loads and the neck fractured with an 'edge-to-edge' pattern despite having minimised any trauma to the femoral head and neck during implantation. On studying the video data, some specimens showed signs of decreased stiffness of the inferomedial portion of the femoral neck which failed slowly in compression producing an 'edge-to-edge' fracture. By contrast, all specimens of good bone quality failed suddenly as an edge-to-out fracture. There were no fractures which began at the medial neck. Biomechanical analysis has shown that by placing the femoral

Fig. 3

Photograph showing fracture patterns. All specimens with a normal bone mineral density failed as 'edge-to-out' fractures (right) and most of the femora with a low bone mineral density as 'edge-to-edge' fractures (left at front).

component in valgus the strain on the upper part of the femoral neck is decreased, but is increased in the lower part.²⁶ In our study only the osteoporotic specimens failed in this region. We therefore hypothesise that the adverse effect of a valgus component in osteoporotic bone can be explained by the diminished resistance of osteoporotic bone in the inferior part of the femoral neck to repetitive compressive stresses.

Throughout our study we attempted to minimise any change in femoral offset since we thought that this might influence fracture stresses. Unfortunately, placing the femoral component in valgus usually reduces the femoral offset³³ in this case by a mean of 2.2 mm (-7.4 to 3.1). Despite this, the protective effect of a valgus position could not be attributed to the decrease in femoral offset, since several specimens showed this protective effect despite an increased offset. Furthermore, there was no correlation between offset and the number of cycles to fracture.

Careful interpretation of our data is required since the fractures were examined *in vitro*. It has been shown that the biomechanical properties of embalmed and fresh bone do not differ significantly.³⁴ We confirmed that there was no correlation between the storage time of the embalmed specimens and the number of cycles to fracture. In addition, each specimen pair acted as its own control, thereby diminishing any possible effect of the embalming process. Hence, the embalming process should not have falsified the results. However, no healing was possible after implantation as would have been the case in an *in vivo* study. In the normal subject loads are not applied repetitively with a constant frequency and fixed direction of force, but our study clearly showed that, for all specimens of normal BMD, valgus placement improved the stress resistance. Furthermore, these results agree with a recently

Fig. 4a

Fig. 4b

Figure 4a – Graph showing that for specimens with osteoporosis placement in 10° of valgus diminished resistance against fracture in all specimens. Figure 4b – Bar chart showing that the fracture cycle for components positioned normally was 6784 cycles and decreased to 4460 cycles for the specimens placed in 10° of valgus (Wilcoxon signed ranks test $p = 0.043$). Whiskers denotes SD and asterisk indicates a significance < 0.05 .

published study by Anglin et al²⁰ which examined the effect of placement of the implant in valgus on fracture of the femoral neck using a single load to fracture and a notched femoral neck. They reported an increase in failure stress of 28% for a 10° valgus placement of the femoral component in samples with good bone quality. Their study, however, showed no adverse effect of valgus placement in specimens of poor bone quality. This difference could be rooted in the fundamental difference between transient and dynamic testing. It may be that osteoporotic bone is less resistant to repetitive compressive stress on the medial femoral neck.

All the prostheses were implanted as planned. Furthermore, the number of load cycles to failure varied between

different specimen pairs. Hence, no quantitative relationship between cycles to fracture and optimal implant-shaft angle could be determined. Further biomechanical studies using dynamic methods will be required. The fact that our study protocol used increasing cyclical loads may complicate statistical analysis. Unfortunately, our preliminary biomechanical testing showed that the cyclical fracture loads of the specimens differed between 700 N and 7000 N. The aim of our study was the simulation of cyclical loading conditions with an identical study protocol for all specimens and thus increasing loads were necessary. Despite this, all our specimens were tested using an identical study protocol and each pair of specimens acted as its own control. Hence we believe that the increasing loads did not influence the analysis of our results.

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References

1. Amstutz HC, Campbell P, Le Duff MJ. Metal-on-metal hip resurfacing: what have we learned? *Instr Course Lect* 2007;56:149-61.
2. McMinn DJ, Treacy R, Lin K, Pynsent P. Metal on metal surface replacement of the hip: experience of the McMinn prosthesis. *Clin Orthop* 1996;329:89-98.
3. Shimmin A, Beaulé PE, Campbell P. Metal-on-metal hip resurfacing arthroplasty. *J Bone Joint Surg [Am]* 2008;90-A:637-54.
4. Beaulé PE, Amstutz HC, Le DM, Dorey F. Surface arthroplasty for osteonecrosis of the hip: hemiresurfacing versus metal-on-metal hybrid resurfacing. *J Arthroplasty* 2004;19:54-8.
5. Treacy RB, McBryde CW, Pynsent PB. Birmingham hip resurfacing arthroplasty: a minimum follow-up of five years. *J Bone Joint Surg [Br]* 2005;87-B:167-70.
6. Daniel J, Pynsent PB, McMinn DJ. Metal-on-metal resurfacing of the hip in patients under the age of 55 years with osteoarthritis. *J Bone Joint Surg [Br]* 2004;86-B:177-84.
7. Heilpern GN, Shah NN, Fordyce MJ. Birmingham hip resurfacing arthroplasty: a series of 110 consecutive hips with a minimum five-year clinical and radiological follow-up. *J Bone Joint Surg [Br]* 2008;90-B:1137-42.
8. McMinn DJ, Daniel J, Ziaee H, Pradhan C. Results of the Birmingham hip resurfacing dysplasia component in severe acetabular insufficiency: a six- to 9.6-year follow-up. *J Bone Joint Surg [Br]* 2008;90-B:715-23.
9. Steffen RT, Pandit HP, Palan J, et al. The five-year results of the Birmingham hip resurfacing arthroplasty: an independent series. *J Bone Joint Surg [Br]* 2008;90-B:436-41.
10. Campbell P, Beaulé PE, Ebrahimpour E, et al. A study of implant failure in metal-on-metal surface arthroplasties. *Clin Orthop* 2006;453:35-46.
11. Marker DR, Seyler TM, Jinnah RH, et al. Femoral neck fractures after metal-on-metal total hip resurfacing: a prospective cohort study. *J Arthroplasty* 2007;22:66-71.
12. Amstutz HC, Campbell PA, Le Duff MJ. Fracture of the neck of the femur after surface arthroplasty of the hip. *J Bone Joint Surg [Am]* 2004;86-A:1874-7.
13. Cossey AJ, Back DL, Shimmin A, Young D, Spriggins AJ. The nonoperative management of periprosthetic fractures associated with the Birmingham hip resurfacing procedure. *J Arthroplasty* 2005;20:358-61.
14. Falez F, Favetti F, Casella F, Panegrossi G. Hip resurfacing: why does it fail?: early results and critical analysis of our first 60 cases. *Int Orthop* 2008;32:209-16.
15. Little CP, Ruiz AL, Harding IJ, et al. Osteonecrosis in retrieved femoral heads after failed resurfacing arthroplasty of the hip. *J Bone Joint Surg [Br]* 2005;87-B:320-3.
16. Morlock MM, Bishop N, Ruther W, Dellling G, Hahn M. Biomechanical, morphological, and histological analysis of early failures in hip resurfacing arthroplasty. *Proc Inst Mech Eng [H]* 2006;220:333-44.
17. Shimmin AJ, Back D. Femoral neck fractures following Birmingham hip resurfacing: a national review of 50 cases. *J Bone Joint Surg [Br]* 2005;87-B:463-4.
18. De Hann R, Campbell PA, Su EP, De Smet KA. Revision of metal-on-metal resurfacing arthroplasty of the hip: the influence of malpositioning of the components. *J Bone Joint Surg [Br]* 2008;90-B:1158-63.
19. Amstutz HC, Beaulé PE, Dorey FJ, et al. Metal-on-metal hybrid surface arthroplasty: two to six-year follow-up study. *J Bone Joint Surg [Am]* 2004;86-A:28-39.
20. Anglin C, Masri BA, Tonetti J, Hodgson AJ, Greidanus NV. Hip resurfacing femoral neck fracture influenced by valgus placement. *Clin Orthop* 2007;465:71-9.
21. Back DL, Dalziel R, Young D, Shimmin A. Early results of primary Birmingham hip resurfacings: an independent prospective study of the first 230 hips. *J Bone Joint Surg [Br]* 2005;87-B:324-9.
22. De Smet KA. Belgium experience with metal-on-metal surface arthroplasty. *Orthop Clin North Am* 2005;36:203-13.
23. Beaulé PE, Dorey FJ, LeDuff M, Gruen T, Amstutz HC. Risk factors affecting outcome of metal-on-metal surface arthroplasty of the hip. *Clin Orthop* 2004;418:87-93.
24. Beaulé PE, Lee JL, Le Duff MJ, Amstutz HC, Ebrahimpour E. Orientation of the femoral component in surface arthroplasty of the hip: a biomechanical and clinical analysis. *J Bone Joint Surg [Am]* 2004;86-A:2015-21.
25. Long JP, Bartel DL. Surgical variables affect the mechanics of a hip resurfacing system. *Clin Orthop* 2006;453:115-22.
26. Radcliffe IA, Taylor M. Investigation into the effect of varus-valgus orientation on load transfer in the resurfaced femoral head: a multi-femur finite element analysis. *Clin Biomech* 2007;22:780-6.
27. Freeman MA. Some anatomical and mechanical considerations relevant to the surface replacement of the femoral head. *Clin Orthop* 1978;134:19-24.
28. Hess T, Gampe T, Kottgen C, Szawlowski B. Intraoperative navigation for hip resurfacing: methods and first results. *Orthopade* 2004;33:1183-93 (in German).
29. Ganapathi M, Evans S, Roberts P. Strain pattern following surface replacement of the hip. *Proc Inst Mech Eng [H]* 2008;222:13-18.
30. Bergmann G, Graichen F, Rohlmann A. Hip joint contact forces during stumbling. *Langebecks Arch Surg* 2004;389:53-9.
31. No authors listed. ISO 7206-4: Implants for surgery: partial and total hip joint prostheses. Part 4: Determination of endurance properties of stemmed femoral components. Geneva: International Organization for Standardization, 2002.
32. Little JP, Taddei F, Viceconti M, Murray DW, Gill HS. Changes in femur stress after hip resurfacing arthroplasty: response. *Clin Biomech* 2007;22:440-8.
33. Beaulé PE, Poitras P. Femoral component sizing and positioning in hip resurfacing arthroplasty. *Instr Course Lect* 2007;56:163-9.
34. Beaupied H, Dupuis A, Arlettaz A, et al. The mode of bone conservation does not affect the architecture and the tensile properties of rat femurs. *Biomed Mater Eng* 2006;16:253-9.