

## Biomechanics of noncemented total hip arthroplasty

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# Biomechanics of noncemented total hip arthroplasty

Rik Huiskes, PhD

Biomechanical research on noncemented total hip arthroplasty has not kept pace with the rate with which new devices have been introduced and tested in the clinic. Although promising clinical results of noncemented total hip arthroplasty are published in the peer-reviewed literature, many problems have been reported as well and long-term follow-up studies are scarce. Due to the variety of fixation methods, component designs, surgical techniques, and indications applied, the problems reported are not easily related to generalized paradigms for failure mechanisms (described as failure scenarios). However, this information is required if general guidelines for prosthetic designs and preclinical tests are to be developed. The problems appear to be concentrated around issues of primary fixation, initial stability and bony incorporation, issues of bone adaptation and periprosthetic resorption, and issues of wear particle reactions and interface loosening. Biomechanical studies have mostly been concentrated on interface mechanics and bone mechanics, as related to problems of fixation and bone remodeling. Recent publications of studies in these areas are reviewed here.

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## Abbreviations

DEXA	dual energy x-ray absorptiometry
RSA	roentgen stereophotogrammetric analysis
THA	total hip arthroplasty

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Of the 24 various brands of noncemented total hip arthroplasty (THA) marketed in the United Kingdom, only three were subject to survival analysis in peer-reviewed journals and of those only one for greater than 5 years [1\*\*]. According to the Swedish Register of THA, which produces the most objective, statistically significant information about the long-term clinical performance of prosthetic designs, the few noncemented designs have not done well, compared with cemented ones [2\*\*]. Concern has arisen over the frequency with which new fixation methods and component designs have been introduced, without proper preclinical and clinical testing [1\*, 2\*\*, 3]. Long-term prospective studies, comparing cemented to noncemented results are rare, and double-blind studies nonexistent, although promising trials have been started [4\*]. Innovations in design have emerged to create problems that are worse than those they were intended to solve [3]. The clinical introduction of noncemented THA over the years has probably occurred too fast, with inadequate controls. On the other hand, however, cemented THA has problems of its own, particularly in young, active patients [5]. In some single-center follow-up series, specific types of noncemented designs have been performing quite well for a number of years [6,7]. The concept of noncemented THA is still promising, if the common causes for its predominant failure modes can be detected and prevented.

The first generic problem of noncemented THA components is their lack of fit, due to variability in the bone anatomy, and to the inherently imprecise drilling, reaming, and rasping procedures commonly used in bone preparation. Lack of fit affects the initial stability of the components and their prospects for timely incorporation and also promotes thigh pain and periprosthetic bone loss due to stress bypasses [3]. The second generic problem is caused by the bulkiness of the noncemented stems. In the load-sharing process between stem and bone, the relative rigidity of each determines its share of load. Hence, a stem of higher rigidity attracts more load, at the expense of the bone. This causes stress shielding, leading to periprosthetic bone loss [3]. The third problem is the particular sensitivity of noncemented reconstructions to loosening as an effect of wear and abrasive particles [8,9]. On the one hand, this may be caused by enhanced particle production due to modularity of the components [10]. Or, it can be accelerated by particle transportation through interface gaps or noningrowth areas [11\*]. Biomechanical research and testing of these problems is proceeding. Recent reports on interface and



bone mechanics, relative to noncemented THA, are discussed below.

### Fixation and interface mechanics

All noncemented femoral components migrate slightly early postoperatively. Many of them gradually stabilize, but some continue to move. An important issue is whether progressive migration is indicative for later loosening. For cemented stems, this was suggested by Mjoberg *et al.* [12], and confirmed by Karrholm *et al.* [13], using highly accurate roentgen stereophotogrammetric analysis (RSA). With the same method, Ryd *et al.* [14] showed this relationship to hold for noncemented tibial components in total knee arthroplasty as well. Karrholm *et al.* [15\*\*] performed RSA on 64 hip reconstructions to monitor migration and rotation of the stem. All stems were of the same design, 20 were cemented, 23 hydroxyapatite, and 21 porous coated. All migrated to some extent during the 24 months of the investigation, of which almost 20% migrated more than 250  $\mu\text{m}$ . Most of the migration occurred within the first 2 months postoperatively. In some cases migration continued to increase (Fig. 1). A greater number of porous than hydroxyapatite-coated stems continued to move, and radiolucency was more frequent in the porous-coated group as well. More direct conclusions about the predictive value of persistent migration were drawn by Freeman and Plante-Bordeneuve [16\*] from a migration study of four groups of the same stem design with cemented, press-fit, and hydroxyapatite-coated fixation, using conventional radiographic measurements. Conventional radiography is on the order of 10 times less accurate than RSA, but revisions could be correlated significantly with excessive migration rates in this study. Although more evidence is needed before, definite conclusions can be drawn, there are strong indications that the fate of revision for stem

loosening at the mid-long term is determined at a very early decisive moment when the curves of migration diverge (Fig. 1). Since all stems migrate early, including the successful ones, this begs the question if it is not primary, but rather secondary stability that counts.

Some light was shed on this question recently by a number of investigators. Cheng *et al.* [17\*] reported results of a study with porous-coated stems in dogs. They found significantly more proximal bone ingrowth and less radiolucency around collarless stems, as compared with collared ones. They concluded that the collar prevents the stem from subsiding and settling in a stable position during the early postoperative recovery period. In a recent clinical report from the Norwegian Register [18\*\*], the authors reported a significant number of early loosening of a noncemented screw-threaded stem. The mechanism for these failures was suggested in an earlier animal experimental study with tapered, screw-threaded, hydroxyapatite-coated stems in the tibial diaphysis of goats [19]. These stems were well fixed during the operation, but the holding power was lost early postoperatively due to interface remodeling and repair. Subsequent rotations caused them to loosen completely. The threads prevented the stems from subsiding and settling in the canal. Similar tapered stems without screw threads, applied later in the same animal model, did not loosen. A third kind of experience is one with screw-threaded cups. Experimental cadaver experiments, in combination with finite-element analysis, showed that these cups produce stresses in the acetabulum during fixation even beyond those of hip-joint loading [20]. These prestresses act to keep the cup secure. However, interface repair and remodeling processes are likely to relax the stresses. The threads will prevent the cup from finding secondary stability. This is the most likely failure scenario for these devices, which are subject to high failure rates [21].

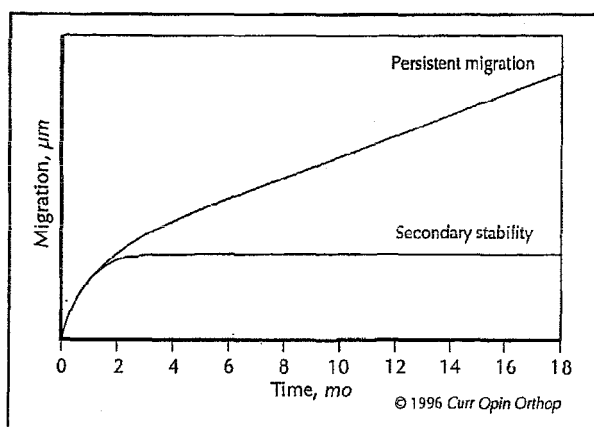


Fig. 1. A generalized, schematic representation of implant migration, based on roentgen stereophotogrammetric analysis studies of several kinds of components. Slight migration always occurs initially; within 2 months, most components have reached secondary stability, but some persist in migration and eventually loosen.

The capacity of a THA component to settle toward secondary stability after some interface resorption is one of the important issues for component incorporation. It depends mostly on its surface contour, and the absence of obstructions, such as collars. Very little biomechanical research on these issues has been reported, although they could successfully be addressed by finite-element analysis. The second important issue for component incorporation is its capacity to maintain secondary stability in the pre-ingrowth phase, instead of persisting in migration. This capacity is bound to depend greatly on the pace of ingrowth and on interface friction. Friction is another area in which very little research has been done, although it is known that the load-transfer mechanism in the femoral reconstruction is very sensitive to interface-friction coefficients [22]. This may explain why uncoated press-fit stems, porous-coated stems, and hydroxyapatite-coated stems respond differently.

## Periprosthetic resorption and bone mechanics

Recently, more information has been provided about the validity of Wolff's law. Owing to the application of pre- and postoperative dual energy x-ray absorptiometry (DEXA) scanning, the relationship of periprosthetic bone loss with stress shielding has been established quite definitely for the femoral reconstruction. Precision of 2.7% to 3.4% is achieved with DEXA measurement of bone mineral density, provided that the patient is carefully positioned, especially in rotation [23]. Korovessis *et al.* [24] found significant average postoperative reductions in bone marrow density around the femoral and acetabular components of the Zweymuller THA, relative to an unoperated control group. Until now, this design was thought by many to be exempt from Wolff's doom, owing to its press-fit fixation. The authors concluded that DEXA is important for the early detection of aseptic loosening. Statements like this are to be found in the literature repeatedly. There is no known proof, however, that gross cortical bone loss is related to loosening, either in this series or in any other. Excessive bone loss in the femur will likely disturb revision operations, but a correlation with early loosening has not been documented as yet.

Hughes *et al.* [25] measured proximal femoral bone mineral density in two series of patients with porous-coated stems of similar design to investigate the effects of titanium versus cobalt-chromium stems. Theoretically, titanium, with an elastic modulus of about 50% of cobalt chromium, produces less stress shielding. The patterns of bone loss reported were consistent with patterns of stress shielding, as generally found in finite-element and experimental studies. Loss of bone was also more extensive around the cobalt-chromium as compared with the titanium stem (average 34% vs 15% in the calcar area, for example). In further statistics the authors left the analysis of paired observations (operated vs nonoperated) for mean bone mineral density per group. Apparently, statistical analysis of these numbers led to the conclusion that cobalt-chromium stems do not provoke proximal femoral bone loss notably more than titanium ones. They generally advocate the use of the cheaper cobalt chromium in noncemented stems. Leaving the statistics for what they are, these authors overlook a general principle of mechanics [26,27\*] (Fig. 2). The rough guidelines shown in this figure imply that the extent of stress shielding depends on the rigidity of the stem relative to that of the bone. They also imply that the differences in effects of titanium and cobalt-chromium stems diminish when either the stem is relatively thin, or the bone is relatively stiff. Conversely, they increase with the thickness of the stem and the flexibility (or porosity) of the bone. Hence their conclusion, that it does not matter may be warranted for the relatively slender prosthesis they investigated, but it is certainly not true in general.

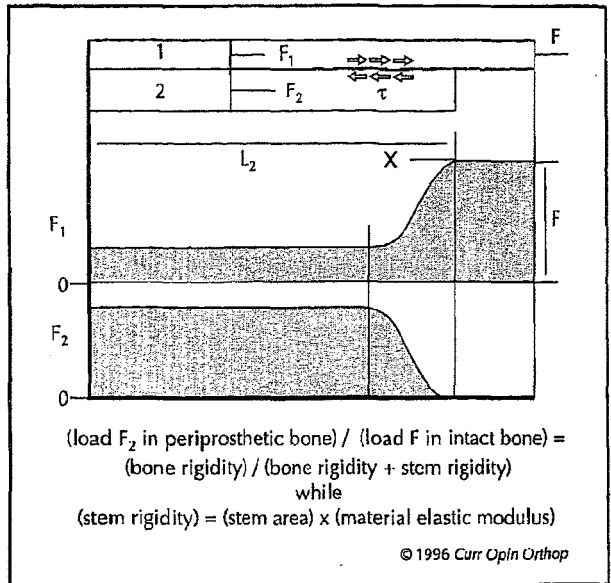


Fig. 2. Load applied to a stem ( $F$ ) is shared with the bone, to a ratio of  $F_1/F_2$ . The intact bone would experience the total load  $F$ , hence the load shielding is  $F - F_2$ . In this simple example the ratio  $F_2/F$  can be calculated directly from the bone and stem rigidities. The formulas reveal that stress shielding is not linearly related to stem cross-sectional area, stem material elastic modulus, and bone rigidity, but that these parameters interact to form a relatively complex relationship. The effect of stem modulus on stress shielding, for example, depends on stem area and bone rigidity as well. It can also be seen that if bone rigidity and stem rigidity are equal, the load shielding is exactly 50%, and not zero, as is often thought. (Modified from Huiskes [26].)

The relationship between stress shielding and bone resorption was also addressed in an article from Pritchett [28\*]. He compared the postoperative reduction in proximal bone mineral density, measured with DEXA relative to the unoperated contralateral femur, for five different prostheses. The overall results were roughly compared to those of experimental strain gauge data published in the older literature. He concluded that the data support the stress shielding paradigm. Skinner *et al.* [29\*\*] studied this question more directly by comparing periprosthetic bone loss in patients with AML stems, measured with DEXA, with predictions of stress patterns, determined in finite-element analysis. The unoperated contralateral bone was used as the control, in both the DEXA and the finite-element analyses. Correlations between DEXA data and finite-element stress values yielded correlation coefficients between 0.75 and 0.89 among the six patients studied. The authors concluded that the extent of eventual periprosthetic bone loss due to stress shielding can be predicted from precise finite-element analyses of the immediate postoperative situation, in comparison with the intact bone.

There is, however, quite a methodologic distance between correlation of stress shielding and bone loss, and prediction of one based on the other. This distance can be bridged by bone remodeling computer simulation methods, based on a combination of finite-element mod-

els and strain-adaptive bone remodeling theory, which provides a quantitative form of Wolff's law. This method simulates the gradual remodeling process from the stress discrepancy between the operated bone and the preoperative intact one. Studies performed to validate the method relative to animal experimental and human retrieval data were reviewed recently [30\*]. Applications of this method have revealed that the extent of bone resorption due to stress shielding is even more sensitive to the stiffness of the bone (density, thickness) than it is to that of the stem [31]. This sensitivity to bone quality was also confirmed in retrieval analysis [32], and partly explains the variety in DEXA data found in patient series. It implies that with the help of preoperative DEXA, bone remodeling simulation studies can estimate the likely amount of long-term postoperative bone loss for individual patients.

Apart from stem and bone rigidity, the stresses in the bone are affected by stem-bone interface conditions [26]. From finite-element analyses of an AML-like stem, Keaveny and Bartel [33\*] found that ingrowth can substantially reduce proximal loading of the bone. This increases the risk for periprosthetic bone resorption and also stem fracture, due to its reduced bone support. They noted that stress shielding is particularly enhanced for thick stems in relatively flexible bones, as also follows from the formulas shown in Figure 2. They conclude that ingrowth coatings should be reduced to the proximal stem area. They also noted that proximal ingrowth does not necessarily prevent interface micromotions of a distal, smooth stem part from occurring. A similar study of a collared stem was published by Skinner *et al.* [34\*]. They concluded that a five eighths proximal coated stem provides the best compromise between the excessive stress shielding of a fully coated stem (despite the collar), and the high interface peak stresses at the tip of one that is one third coated. The effects of ingrowth coating area on periprosthetic bone loss were further substantiated in a study of an osteonics type stem (Osteonics Corp., Allendale, NJ) by Weinans *et al.* [35\*\*], using finite-element analysis in combination with bone remodeling simulation. The amount of bone resorption predicted was less for a one third proximal coating as compared with a fully coated stem. The numbers reduced further when a thin proximal coating band was assumed. As in all the above clinical, experimental, and finite element studies, the actual numbers found may be different for alternative stem shapes, interface bonding conditions, and stem- to-bone rigidity ratios.

Another interface condition that affects load transfer, and thus the risks for periprosthetic bone loss, is stem fit. The effects of fit on bone stresses for prostheses without collar were discussed by Hua and Walker [36\*], based on laboratory experiments with postmortem bones. Bone

strains were determined using photoelastic coatings. The effects of press fitting were well illustrated by a symmetric smooth stem, which produced proximal bone strain values similar to those in the intact femur. Stress shielding was apparent only further down. When this same stem was cemented and tested again, proximal strains were also much lower than in the intact bone (mean, 20% to 30%). This is caused by the bonding effect of the cement, which prevents the stem from subsiding when loaded, necessary for press fitting. Ingrowth at a later stage will also produce this effect. This is also the reason that bone remodeling around press-fit stems tends to proceed nonmonotonously [37,38]. Initially, there is bone formation proximally, which results in resorption later. Hua and Walker [36\*] also found that precise fit, produced by custom-made press-fit stems, provoked more natural bone strains than average fit. In the study of Weinans *et al.* [35], dramatic resorption was predicted for the case of a noningrown stem that would jam in the distal canal and develop a fibrous interface proximally. Clinical evidence for such a stress-bypass mechanism was reported recently, based on a study of an isoelastic stem [39\*]. Conversely, much less bone would be resorbed if the stem was press-fitted proximally, with a gap around the distal stem.

A prerequisite for the press-fit stems to load the femur is the capacity to subside, if only slightly, when loaded. It stands to reason that this capacity would be prevented by the presence of a collar, as discussed in the previous section. This effect was studied by Jasty *et al.* [40\*\*] in experimental strain-gauge analyses on postmortem bones implanted with collared stems. They compared the effects of press fit, loose fit, and precise fit at the isthmus. In the case of press fit, the calcar was apparently not fully loaded, which caused proximal bone stresses to be reduced by a mean 39% relative to normal. In the case of loose fit, the calcar was fully loaded, probably due to easy subsidence of the stem. This produced excessive proximal bone stresses of a mean 141% relative to normal. In the case of precise fit, fixation was apparently shared between collar-calcar and stem contact, with nearly normal bone stresses as a result. This original work nicely illustrates the dependence of collar efficacy on surgical technique, although the authors do not emphasize this explicitly. Of course, the conclusions are limited to the immediate postoperative situation. Interface remodeling and repair processes will likely affect the mechanical interface conditions, as discussed above. Manley *et al.* [41\*\*] reported that no significant differences were found in proximal femoral strains in dogs, after 4 months' implantation of collared and collarless stems of the same design. There was, however, a significant difference in cortical porosity (collarless 8.2% vs collared 5.8%). The same authors published another paper [42\*], based on similar experiments (or possibly the same), in which they reported

no significant differences in bone elasticity or density after the same 4-month period, when comparing collared to collarless. This appears to be confusing, but it is probably fair to conclude from their work that the collar had no notable effect on periprosthetic bone loss, due to the stem ingrowth process, by which the calcar became unloaded.

### Implications for total hip arthroplasty design and application

Both clinically and biomechanically noncemented THA still leaves much to be investigated. Nevertheless, some general paradigms explaining their behavior are taking shape. Much clarity has been provided regarding the issues of bone loss in the femur at large in relation to Wolff's law. Its relation to stress shielding is fairly well established. This means that the long-term patterns of resorption can be estimated fairly accurately from remodeling analyses, using preoperative bone dimensions and density, stem shape, stem material, fit, and ingrowth characteristics as information. The most useful information for the surgeon can be provided by preoperative DEXA scans. If the femur is unusually thin or the density low, the patient is at risk with a noncemented stem, and a cemented alternative should be considered. Collars on femoral components, although enhancing proximal load transfer in principle, are probably not helpful. They may jeopardize fit of the stem, and the calcar stressing is likely to disappear with stem ingrowth. Coatings should be placed proximally, at least when bone resorption is to be minimized. In situations in which stem design and stress shielding are concerned, the more flexibility the better.

There are, however, inherent contradictions in the above guidelines. What minimizes stress shielding and bone resorption does not necessarily improve fixation stability [43\*]. The paradigm of secondary stability dictates that the stem should be able to slightly subside without obstruction, and without losing conformity with the bone bed. This should be required for both axial and torsional loading. In German mechanics this is called a *force closed* as opposed to a *form closed* fixation. This implies a collarless stem. Uncoated press-fit designs may stress the bone, thereby reducing stress shielding, but the stresses will soon relax due to interface remodeling and repair. Since no ingrowth is provided in this case, they may persist in migrating and eventually will loosen. A proximal coating reduces stress shielding, but a full coating provides more opportunity for bone ingrowth and more friction. Hence, a full coating enhances the holding power of the stem in the pre- and postingrowth phases. It also reduces the pathways for wear debris and the opportunities for osteolysis. While a flexible stem reduces stress shielding, it also increases the tendencies for interface micromotion (Fig. 3). Hence, many design parameters are subject to incompatible design goals [3]. Relative to

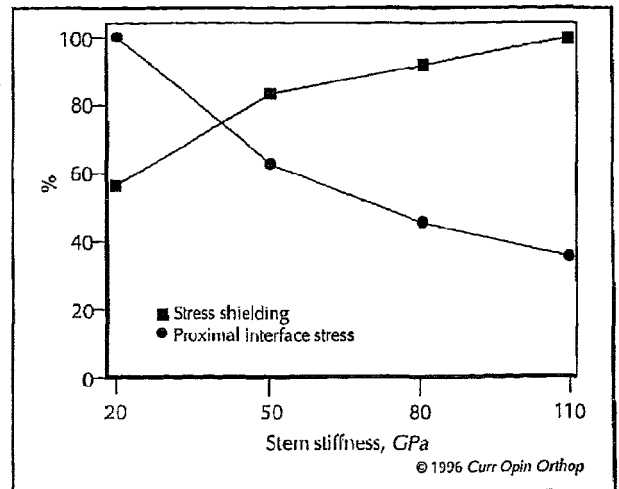


Fig. 3. Stress shielding represents a tendency for bone resorption and interface stress a tendency for interface micromotion. The curves illustrate that requirements for minimal interface motion and minimal bone loss provide incompatible design goals for stem stiffness. A compromise is necessary. (Modified from Huiskes [3].)

the incompatible requirements for minimal bone loss and interface stability, optimal compromises for these parameters must be sought. Bone loss is a conceptual clinical problem, and quite predictable, while failing interface stability is an actual one, and very unpredictable. Hence, it would probably be wise to stay on the safe side of loosening prevention, when these compromises are translated into actual prosthetic components.

The acetabular cup has been somewhat neglected in biomechanical research. There is no reason to assume that the paradigms for stem behavior suggested above are not equally important for the cup. It is likely that Wolff's law works here too, and some evidence of that can be found in the literature [24]. Secondary stability and lack of pathways for debris are also likely to play important roles in interface stability. The ways in which this could translate to some generalized proposals for designs, however require more research.

### References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

- \* Of special interest
  - \*\* Of outstanding interest
1. Murray DW, Carr AJ, Bulstrode CJ: Which primary total hip replacement? *J Bone Joint Surg Br* 1995, 77:520-527.

Identifies 62 different THA types, of which 24 are noncemented. Only one of these was the subject of survival analysis for longer than 10 years in a peer-reviewed article. Two were subjects of survival analysis over a follow-up period of 10 years. Four others were investigated clinically or radiologically after particular time periods. However, 17 of the 24 had never been assessed in peer-reviewed journals.

2. Malchau H: *On the Importance of Stepwise Introduction of New Hip Implant Technology; Assessment of Total Hip Replacement Using Clinical Evaluation, Radiostereometry, Digitized Radiography and a National Hip*

Registry [Thesis]. Goteborg, Sweden: Joint Replacement Unit, Sahlgrenska University Hospital; 1995.

This PhD dissertation is based on five original articles that emphasize the usefulness of roentgen stereophotogrammetric analysis in the assessment of THA performance.

3. Huiskes R: **Failed innovation in total hip replacement.** *Acta Orthop Scand* 1993, 64:699-716.
4. Rorabeck CH, Bourne RB, Laupacis A, Feeny D, Wong C, Tugwell P, Leslie K, Bullas R: **A double-blind study of 250 cases comparing cemented with cementless total hip arthroplasty: cost-effectiveness and its impact on health-related quality of life.** *Clin Orthop* 1994, 298:157-164.
5. Geesink RGT, Hoefnagels NHM: **Long-term results of total hip arthroplasty in young patients.** *Curr Opin Orthop* 1995, 6:32-37.
6. Geesink RGT, Hoefnagels NHM: **Six-year results in hydroxyapatite-coated total hip replacement.** *J Bone Joint Surg Br* 1995, 77:534-547.
7. Engh CA, Hooten JP, Zettl-Schoffar KF, Ghaffarpour MG, McGovern TF, Bobyn JD: **Evaluation of bone ingrowth in proximally and extensively porous-coated anatomic medullary locking prostheses retrieved at autopsy.** *J Bone Joint Surg Am* 1995, 77:903-910.
8. Harris WH: **Osteolysis and particle disease in hip replacement.** *Acta Orthop Scand* 1994, 65:113-123.
9. McKellop HA: **Wear modes, mechanisms, damage and debris.** In *Total Hip Revision Surgery*. Edited by Galante JO, Rosenberg AG, Callaghan JJ. New York: Raven Press; 1995.
10. Bobyn JD, Tanzer M, Krygier JJ, Dujovne AR, Brooks CE: **Concerns with modularity in total hip replacement.** *Clin Orthop* 1994, 298:27-36.
11. Goelz DD, Smith EJ, Harris WH: **The prevalence of femoral osteolysis associated with components inserted with or without cement in total hip replacements.** *J Bone Joint Surg Am* 1994, 76:1121-1129.

In a retrospective matched-pair radiographic study of femoral stem fixation, these authors found osteolysis in 29% in a group of 41 noncemented cases, and none in a matched group of cemented ones. They attribute the osteolytic phenomena to wear debris and stress the importance of debris transportation through the interface, as opposed to debris production.

12. Mjoberg B, Brismar J, Hansson LI: **Definition of endoprosthetic loosening: comparison of arthrography, scintigraphy and roentgen stereophotogrammetry in prosthetic hips.** *Acta Orthop Scand* 1985, 56:469-473.
13. Karholm J, Borssén B, Lowenhielm G, Snorrason F: **Does early micromotion of femoral stem prostheses matter? Four- to 7-year stereoradiographic follow-up of 84 cemented prostheses.** *J Bone Joint Surg Br* 1994, 76:912-917.
14. Ryd L, Albrektsson BEJ, Carlsson L, Dansgürd F, Herberts P, Lindstrand A, Regner L, Toksvig-Larsen S: **Roentgen stereophotogrammetric analysis as a predictor of mechanical loosening of knee prostheses.** *J Bone Joint Surg Br* 1995, 77:377-383.
15. Karholm J, Malchau H, Snorrason F, Herberts P: **Micromotion of femoral stems in total hip arthroplasty: a randomized study of cemented, hydroxyapatite-coated and porous-coated stems with roentgen stereophotogrammetric analysis.** *J Bone Joint Surg Am* 1994, 76:1692-1705.

In a 2-year study, the migrations of cemented, hydroxyapatite-coated and porous-coated stems of the same design were measured. Subsidence of over 250  $\mu$ m could be established with 99% certainty, owing to the precision of this method. Increased subsidence of a mean 1000 and 2000  $\mu$ m were found for cemented and porous-coated fixation, respectively. Hydroxyapatite seems to enhance early fixation. All stems, however, did migrate to some extent in the early postoperative period, indicating the importance of gradual settling.

16. Freeman MAR, Plante-Bordeneuve P: **Early migration and late aseptic failure of proximal femoral prostheses.** *J Bone Joint Surg Br* 1994, 76:432-438.

Conventional radiography was used to measure migration of stems with a follow-up of more than 5 years. Cemented, press-fit, and hydroxyapatite-coated stems of the same design were studied. Migration of over 1200  $\mu$ m during the first 2 years predicts late aseptic loosening. Here again all stems did migrate to some extent. In most cases this motion does not progress, but in some cases it apparently cannot be constrained by the bone, and leads to failure.

17. Cheng SL, Davey JD, Inman RD, Binnington AG, Smith TJ: **The effect of the medial collar in total hip arthroplasty with porous-coated components inserted without cement.** *J Bone Joint Surg Am* 1995, 77:118-123.

In canine experiments, porous-coated stems without collars had significantly more bony ingrowth than collared ones of the same design. The authors hypothesize that the collar prevents the stem from settling in a stable position, during early dynamic loading.

18. Havelin LI, Espehaug B, Vollset SE, Engesaeter LB: **Early aseptic loosening of uncemented femoral components in primary total hip replacement: a review based on the Norwegian Arthroplasty Register.** *J Bone Joint Surg Br* 1995, 77:11-17.

A report from the Norwegian National Hip Register on 2907 noncemented THAs implanted from 1987 to 1993. At 4.5 years the probability of revision varied between about 1% and 20% for the different types used. The worst results were those of a screw-threaded stem (right hips only). (I believe that the significance of a lack of settling capacity is demonstrated here in a dramatic way.)

19. Van Loon PJM, Weinans H, Huiskes R, De Groot K, Slooff TJJH: **Intramedullary fixation with screwed, conical stems: unsolicited results from animal experiments.** *Clin Materials* 1992, 10:239-242.
20. Dalstra M, Huiskes R: **Prestresses around the acetabulum generated by screwed cups.** *Clin Materials* 1994, 16:145-154.
21. Yehiro MA, Gantenberg JB, Nelson R, Lu HTC, Mishra NK: **Comparison of the results of cemented, porous-ingrowth, and threaded acetabular cup fixation.** *J Arthroplasty* 1995, 10:339-350.
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25. Hughes SS, Furia JP, Smith P, Pellegrini VD: **Atrophy of the proximal part of the femur after total hip arthroplasty without cement.** *J Bone Joint Surg Am* 1995, 77:231-239.
26. Huiskes R: **Biomechanics of artificial joint fixation.** In *Basic Orthopaedic Biomechanics*. Edited by Mow VC, Hayes WC. New York: Raven Press; 1991.
27. Bobyn JD, Tanzer M, Dujovne AR, Brooks CE: **Risk factors for stress shielding and bone resorption after cementless total hip arthroplasty.** In *Total Hip Revision Surgery*. Edited by Galante JO, Rosenberg AG, Callaghan JJ. New York: Raven Press; 1995.

A concise review of clinical information about the relationship between stress shielding in femoral THA and periprosthetic bone resorption. The author rightfully emphasizes the importance of preoperative bone density for postoperative bone loss. The point is also made that very few clinical problems arising from periprosthetic bone loss have actually been reported.

28. Pritchett JW: **Femoral bone loss following hip replacement.** *Clin Orthop* 1995, 314:156-161.

Using DEXA scanning, 50 THAs of five different prosthetic types were monitored for periprosthetic bone mineral density. Bone losses after more than 3 years were compared with expectations for proximal stress and strain, derived from biomechanical studies in the literature. The conclusion is suggested that the amount of bone loss in individual cases is proportional to stress shielding. This article demonstrates the efficacy of DEXA for clinical trials of THA, and gives useful information about specific prostheses.

29. Skinner HB, Kilgus DJ, Keyak J, Shimaoka EE, Kim AS, Iypton JS: **Correlation of computed finite element stresses to bone density after remodeling around cementless femoral implants.** *Clin Orthop* 1994, 305:178-189.

The authors find good correlation between periprosthetic bone mineral density in six retrieved THAs and the stresses determined in corresponding finite-element models. These findings lend confidence to the stress-shielding paradigm, and suggest the feasibility of finite-element analyses for predictive purposes.

30. Huiskes R: **Bone remodeling around implants can be explained as an effect of mechanical adaptation.** In *Total Hip Revision Surgery*. Edited by Galante JO, Rosenberg AG, Callaghan JJ. New York: Raven Press; 1995.

A concise review of strain-adaptive bone remodeling theories applied in finite-element models to predict the actual amount of long-term periprosthetic bone loss in

THA, based on information about prosthetic design and material characteristics, preoperative bone density, and bone geometry.

31. Huiskes R, Weinans H, Van Rietbergen B: The relationship between stress shielding and bone resorption around total hip stems and the effects of flexible materials. *Clin Orthop* 1992, 274:124-134.
32. Engh CA, McGovern TF, Bobyn JD, Harris WH: A quantitative evaluation of periprosthetic bone-remodeling after cementless total hip arthroplasty. *J Bone Joint Surg Am* 1992, 74:1009-1020.
33. Keaveny TM, Bariel DL: Mechanical consequences of bone ingrowth in a hip prosthesis inserted without cement. *J Bone Joint Surg Am* 1995, 77:911-923.

Using finite-element analysis, the authors show that bony ingrowth decreases the proximal stresses around a hip stem.

34. Skinner HB, Kim AS, Keyak JH, Mote CD: Femoral prosthesis implantation induces changes in bone stress that depend on the extent of porous coating. *J Orthop Res* 1994, 12:553-563.

Using finite-element analysis, the authors determine stresses in periprosthetic bone around a hip stem, depending on the coating extent. They conclude that a five eighths proximal coating provides a good compromise between stress shielding in proximal bone and excessive stresses near the tip of the stem. These results are likely to be specific for the AML stem they analyzed.

35. Weinans H, Huiskes R, Grootenboer HJ: Effects of fit and bonding characteristics of femoral stems on adaptive bone remodeling. *J Biomech Eng* 1994, 116:393-400.

Using strain-adaptive bone-remodeling theory in combination with finite-element models, the authors demonstrate the effects of coating extent and stem fit on long-term periprosthetic bone loss. The predicted amount of bone loss due to proximal undersizing of the stem, resulting in a distal jam and a proximal stress bypass, are particularly impressive. This suggests that surgical technique, in addition to stem design, is a significant factor for postoperative bone integrity.

36. Hua J, Walker PS: Closeness of fit of uncemented stems improves the strain distribution in the femur. *J Orthop Res* 1995, 13:339-346.

Based on a photoelastic coating technique, the authors compare strains on femoral bone surfaces for symmetric, asymmetric, and custom-made stems. The latter were produced for each bone individually, using a computer-aided design (CAD) system. They found that the CAD stems provide proximal strains most similar to the intact bone. These results are probably dependent on the press-fit wedging effect of the stem, in relation with the smoothness of its surface.

37. Van Rietbergen B, Huiskes R, Weinans H, Sumner DR, Turner TM, Galante JO: The mechanism of bone remodeling and resorption around press-fitted THA stems. *J Biomech* 1993, 26: 369-382.

38. Sumner DR, Turner TM, Urban RM, Galante JO: Experimental studies of bone remodeling in total hip arthroplasty. *Clin Orthop* 1992, 276:83-90.

39. Niinimäki T, Jalovaara P: Bone loss from the proximal femur after arthroplasty with an isoelectric femoral stem. *Acta Orthop Scand* 1995, 66:347-351.

Bone-mineral density measurements around 25 isoelectric stems, mean 8.5 years follow-up, were compared with the contralateral side. Proximal bone loss of 14% is attributed to stress bypass, due to the distal wedging of the stem in combination with proximal loosening.

40. Jasty M, O'Connor DC, Henshaw RM, Harrigan TP, Harris WH: Fit of the uncemented femoral component and the use of cement influence the strain transfer to the femoral cortex. *J Orthop Res* 1994, 12:648-656.

Using cadaveric femurs in a laboratory model, these authors investigated the effects of fit of a collared stem on femoral strains. Both press-fit and loose fit at the isthmus level alter the normal strain patterns, but precise fit keeps them similar to the intact bone. This work illustrates the dependence of collar loading efficacy on surgical technique, but the authors do not make that point.

41. Manley PA, Vanderby R, Kohles S, Markel MD, Heiner JP: Alterations in femoral strain, micromotion, cortical geometry, cortical porosity, and bony ingrowth in uncemented collared and collarless prostheses in the dog. *J Arthroplasty* 1995, 10:63-73.

No effects of a collar were found with respect to stem stability and femoral surface strains in laboratory testing of canine THAs, after implantation of 4 months. Somewhat more proximal cortical porosity was found in the collarless group. It is likely that the collar loads the femur in the initial postoperative period, when the stem has not as yet grown in. Collar-calcaneal load transfer is probably relieved later.

42. Kohles SS, Vanderby R, Ashman RB, Manley PA, Markel MD, Heiner JP: Ultrasonically determined elasticity and cortical density in canine femora after hip arthroplasty. *J Biomech* 1994, 27:137-144.

A somewhat different conclusion is reached by these authors who found no effect of the collar on bone elasticity or density.

43. Huiskes R, Van Rietbergen B: Preclinical testing of total hip stems: the effects of coating placement. *Clin Orthop* 1995, 319:64-76.

Using strain adaptive bone remodeling theory in combination with finite-element analysis, the authors studied the effects of coating placement on periprosthetic bone remodeling and interface load transfer. Reduced proximal coatings limit stress shielding, but increase interface stresses. A balance must be found in stem design. Periprosthetic bone remodeling tends to gradually reduce the interface failure probability. Due to trabecular densification and cortical porosity, press-fit stems tend to initially increase proximal bone mass and later reduce it.