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## FACTORS IN THE MECHANICAL FAILURE OF THE FEMORAL COMPONENT IN TOTAL HIP PROSTHESIS

*Report of Six Fatigue Fractures of the Femoral Stem and Results  
of Experimental Loading Tests*

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Total hip prostheses as a method of surgical treatment of osteoarthrosis are being implanted at a significantly increasing rate.

Although the short term results are promising, the late results and late complications are as yet not well documented. As far as mechanical problems are concerned, attention has been focused on wear at the articulating surfaces and skeletal fixation of the prosthesis.

This paper is concerned with another type of mechanical problem: fatigue fractures of the femoral stem. A report on the operative, radiological and metallurgical findings in our cases of stem fracture is presented. Experimental loading tests have been conducted in an attempt to clarify some aspects of this mechanical failure.

### CLINICAL MATERIAL

From a total of 56 replacement arthroplasties of the Charnley-Muller type, Co, Cr, Mo, casting alloy: Protasul (C 0.2-0.3 per cent - S 1 per cent - Mn 1 per cent - Fe 2 per cent - Mo 5-6 per cent - Cr 25.5-29 per cent - Co Rest) there were fatigue fractures of the femoral stem in six cases. We have not, as yet, experienced this complication in any patients from an earlier series of McKee-Farrar or a later series of Charnley stainless steel prostheses.

All six patients had apparently had successful replacements and then experienced a sudden onset of pain and a feeling of instability in the affected leg on weight-

Table 1.

Case	Age at surgery	Result	Fracture of the stem	Clinical symptoms after failure	Revision
Case 1	68	Painfree No external support	(Dec. 1968-July 1970) 20 months postoperatively.	Sudden onset of pain and instability. Could only walk with a cane.	Cracks in the acrylic mantle but no discontinuity.
Case 2	65	Painfree Walking with a cane	(June 1969-Sept. 1971) 27 months postoperatively.	Pain and instability. Sudden onset of the complaints after a painfree interval.	Not necessary.
Case 3	67	Painfree Walking with a cane	(May 1970-Dec. 1971) 19 months postoperatively.	Pain at the hip and the knee. Instability. Sudden onset of complaints.	The stem is not completely surrounded by an acrylic mantle (cfr. picture 3).
Case 4	63	Painfree No external support	(Jan. 1970-Aug. 1971) 18 months postoperatively.	Pain and instability. Sudden onset of complaints.	Cracks in the acrylic mantle but no discontinuity.
Case 5	71	Painfree No external support	(May 1970-Aug. 1972) 27 months postoperatively.	Instability. Sudden onset	No revision necessary.
Case 6	74	Painfree No external support	(May 1971-Jan. 1973) 20 months postoperatively.	Pain on weight bearing. Instability. Sudden onset of complaints.	Revision and replacement by a new prosthesis.

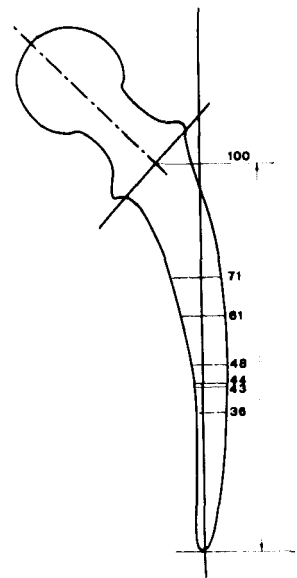
*Figure 1. X-ray check 20 months postoperatively. Failure of the stem at the limit of the upper and middle third.*



*Figure 2. Case 2. X-ray check 27 months postoperatively reveals the fracture at the limit of the distal and middle third.*



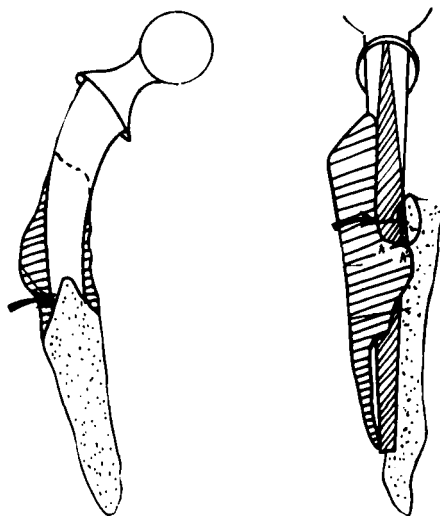
*Figure 3. X-ray film 19 months postoperatively reveals the fracture in the middle third of the stem and angulation of the fragments.*



*Figure 4. The level of the different stem fractures is indicated. A concentration of the levels of failure in the middle third of the stem is noticed.*



*Figure 5 A. The acrylic mantle, removed at the time of revision through a large window in the lateral cortex, did not circumscribe the entire stem.*

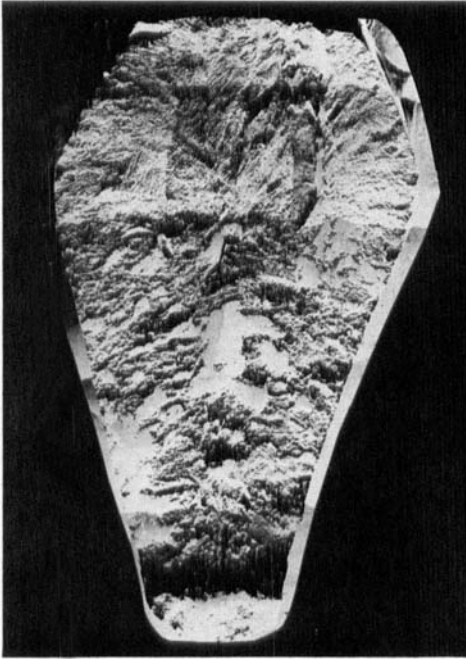


*Figure 5 B. Reconstruction of the relationship of the stem and the acrylic mantle shows the incomplete covering. Particularly the fact that the upper medial edge of the stem is not in contact with cement can cause an unfavourable loading configuration. The arrow indicates the level of the fracture at the femoral stem.*

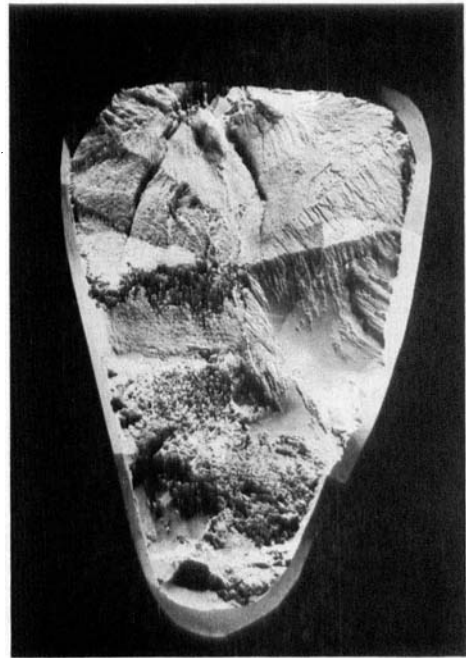
bearing. The details of the failures are summarized in Table 1. All prostheses failed between eighteen and twenty-seven months post-operatively.

Radiographs taken after the onset of pain revealed fractures of the stem of the femoral component with some displacement of the fracture ends, indicating that the metal was not immobilized by the surrounding acrylic (Figures 1, 2 and 3). The sites of failure, in terms of percentage of stem length measured from distal to proximal, are shown in Figure 4. The failure site ranged in level from 36 per cent to 71 per cent of the stem length with three of the six failing at  $45 \pm 3$  per cent of the stem length. The radiographs revealed no abnormal relationship between the femoral stem and acetabular cup nor any malposition of the femoral component.

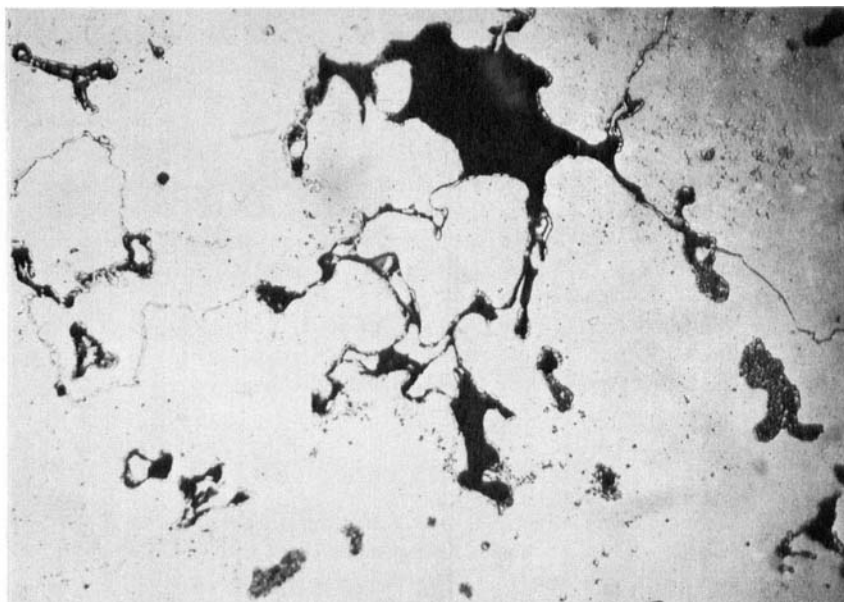
A common finding in all failed cases, however, was that the femoral stem was tilted outwards with regard to the axis of the medullary canal and the tip was near the lateral femoral cortex.



*Figure 6. S.E.M. picture by a Cambridge Stereoscan showing the different pattern of failure of the outer third representing the initiating fatigue zone. The remaining two thirds of the cross section shows a brittle fracture pattern.*



*Figure 7. S.E.M. picture of the fracture site of the stem (case 3). The outer two thirds of the cross section failed in fatigue and the remaining part followed with a brittle fracture at the time the cross section was weakened enough to allow a sudden brittle fracture of the inner third of the area.*



*Figure 8. Metallurgical examination shows microvoids of different sizes in the material near the fracture site. Magnification 460  $\times$ .*

A review of the radiographs from non-fractured cases revealed a variation in the inclination of the femoral stem in the medullary canal.

*Operative findings:* Four of the six cases came to revision because of pain and instability; two had insufficient complaints to warrant exploration. In three of the four cases explored, the femoral prostheses were removed by resection of a large piece of the lateral cortex and an assessment of the acrylic could be made. The other case had the femoral component removed from above.

Two cases demonstrated cracking of the acrylic. Incomplete covering of the femoral stem by the acrylic mantle was seen in the third case and failure occurred at the edge of the defect in the acrylic mantle (Figure 5 A and B).

*Metallurgical studies:* Three of the failed femoral components were studied with a Cambridge scanning electron microscope and with a Reichert MeF2 microscope. The latter study was done after the specimens were prepared by grinding and polishing on diamond cloth, followed by chemical or electrolytical etching.

Examples of the scanning EM findings are shown in Figures 6 and 7. These demonstrate a fatigue failure of the lateral side of the cross section followed by a brittle fracture of the remainder.

The metallographic examination revealed a coarse grained cast structure with typical basaltic crystals, of a mean diameter of 1 mm, which met in the middle. These crystals formed a mosaic pattern with scattered rather than longitudinal orientation. Several microvoids were seen (Figure 8). As shown in Figure 9 A and B precipitations of eutecticum and impurities at the grain boundaries were also

seen. These probably represent a brittle  $\sigma$ -phase which is especially prone to occur in cast cobalt alloys. The precipitation of this  $\sigma$ -phase can be caused by the presence of impurities or by inappropriate previous thermal or mechanical treatment.

A heat treatment was carried out on a specimen at 1300° C for one hour. This treatment caused the complete dissolution of the eutecticum and partial disappearance of the precipitations at the grain boundaries (Figure 10). After this thermal treatment only electrolytic etching could make the grain boundaries visible. A compression test showed that thermal treatment (1300° C—1 hour) increased the yield stress ( $\sigma_{0.2}$ ) of the material in spite of grain growth which normally decreases the yield stress.

In summary it can be stated that grain size, grain structure and phases appearing in these specimens are unfavourable for a material that is exposed to impact load, while the microvoids observed represent an incidental danger.

### EXPERIMENTAL STUDY

Because mechanical factors as well as material properties may be involved in the failure of these prostheses, an experimental model was designed to test some of these factors.

The aim of the experimental study was to obtain an approximation of the stresses at the outer surface of the femoral stem *in vivo* where cracks in the acrylic or incomplete covering of the stem by the acrylic cause an unfavourable loading configuration, yielding high tensile stresses at the site of the discontinuity in the acrylic mantle.

In order to obtain more meaningful data two types of prostheses were tested under the same experimental conditions. The two types were the Charnley Prosthesis (Stainless steel 316 LVM—ASTM F-138) Zimmer Company and the Charnley Muller prosthesis Co, Cr, Mo cast alloy; Protasul (C 0.2–0.3 per cent – S 1 per cent – Mn 1 per cent – Fe 2 per cent – Mo 5–6 per cent – Cr 25.5–29 per cent Co Rest). This allows comparison and relative figures where the results as such cannot be applied to the clinical situation.

### METHODS

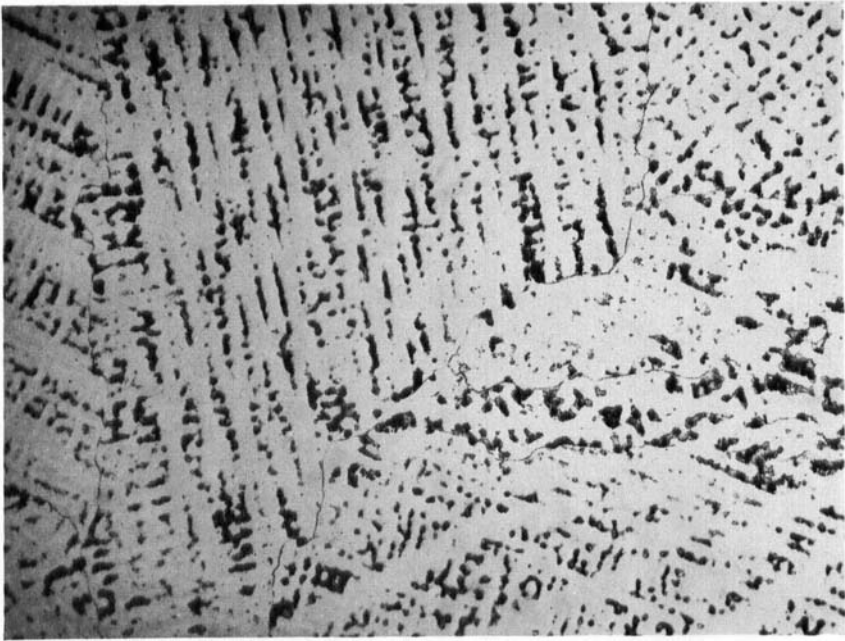
The femoral component of a Charnley Muller Protasul and a stainless steel Charnley prosthesis were imbedded at their stem in an epoxy (Technovit) (Figure 11). The level of imbedding was 57 per cent of their stem length and the stem was mounted vertically so that the applied load on the femoral head at 0° was parallel to the axis of the femoral stem (Figure 12).

The specimen was loaded by an Instron testing machine at the femoral head

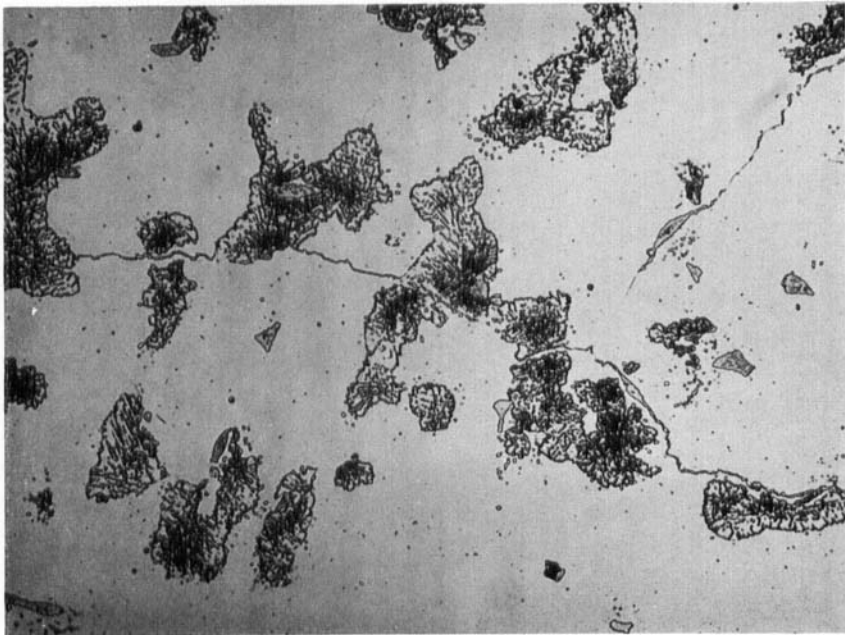
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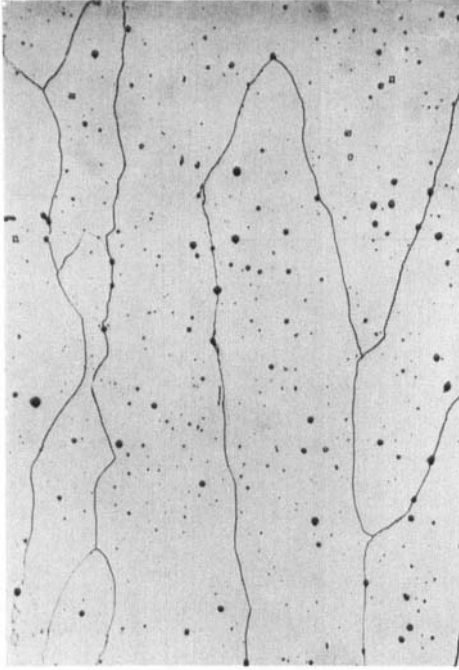
*Figure 9 A and B. Metallography shows the coarse size. Eutecticum and precipitations are observed at the grain boundaries.*



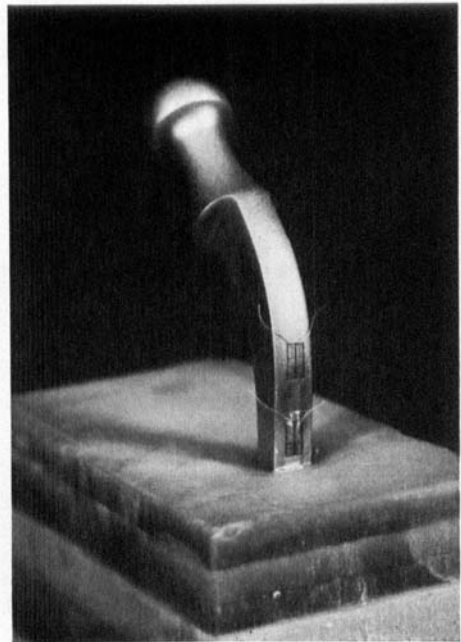
*Figure 9 A. Magnification 60 ×.*



*Figure 9 B. Magnification 450 ×.*



*Figure 10. Metallography after thermal treatment (1300°C-1 hour) shows that the eutecticum is completely dissolved and the precipitations at the grain boundaries have almost completely disappeared.*



*Figure 11. Shows the mounting of the femoral component in the epoxy (Technovit). The level is 57 per cent of the height of the femoral stem and two strain gauges are sealed on the outer base at an identical relative height for both prostheses.*

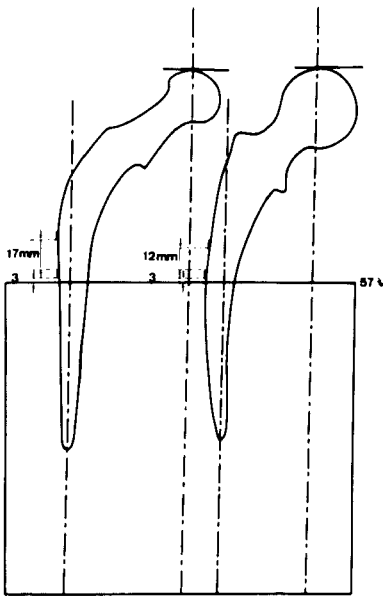


Figure 12. Shows the level of imbedding at 57 per cent of the stem height and the location of the strain gauges. It also demonstrates the  $\pm 20$  per cent difference in bending moment arm at the stem being the perpendicular distance between the application line of the experimental loading force and the axis of the stem.

This does not necessarily represent the moment arm of the resultant joint reaction force in vivo where the direction of the resultant force at the femoral head will be influenced by the possible action of the abductor muscles.

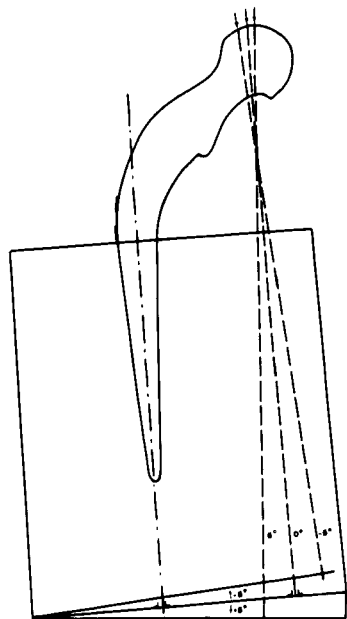


Figure 13. Shows the different experimental loading directions in order to evaluate the influence of the inclination of the stem axis with regard to the axis of the femoral shaft.

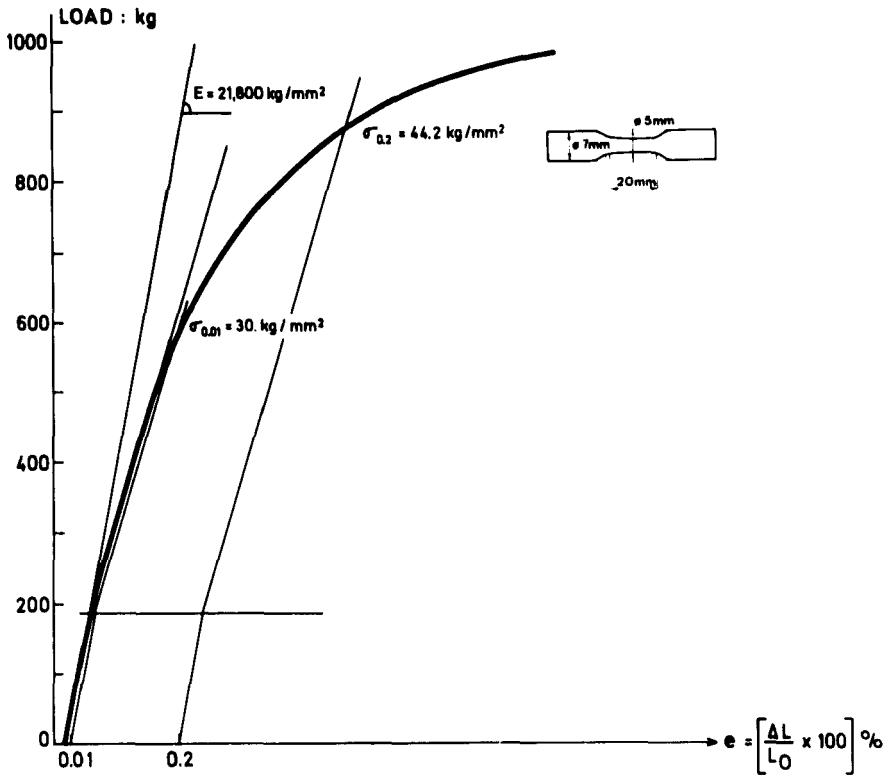


Figure 14 A. A material specimen taken from a Charnley Muller Prosthesis was tested in tension in order to determine:

- the modulus of elasticity ( $E = 21,800 \text{ kg/mm}^2$ ),
  - the 0.01 yielding point ( $\sigma_{0.01} = 30 \text{ kg/mm}^2$ ),
  - the 0.2 yielding point ( $\sigma_{0.2} = 44.2 \text{ kg/mm}^2$ ).
- The ultimate tensile strength is  $72.6 \text{ kg/mm}^2$ .

with interposition of Teflon sheets in order to avoid friction. The cross-head speed was 0.02 cm/min.

Two strain gauges were sealed on the lateral surface at an identical relative position on the stem (Figure 12). The loading at the femoral head was applied in three different directions; parallel to the axis of the stem ( $0^\circ$ ) and with a valgus ( $-5^\circ$ ) and varus ( $5^\circ$ ) position of the stem towards the loading application line (Figure 13). This variation in loading direction towards the femoral stem was applied in order to evaluate the effect of inclination of the femoral stem with regard to the femoral shaft axis. The degree of possible deviation of the stem from the axis of the femur in the frontal plane is dependent upon the width of the medullary canal but measurements demonstrate that a possible tilting over  $\pm 5^\circ$  is a realistic average figure. The modulus of elasticity and the yielding point were

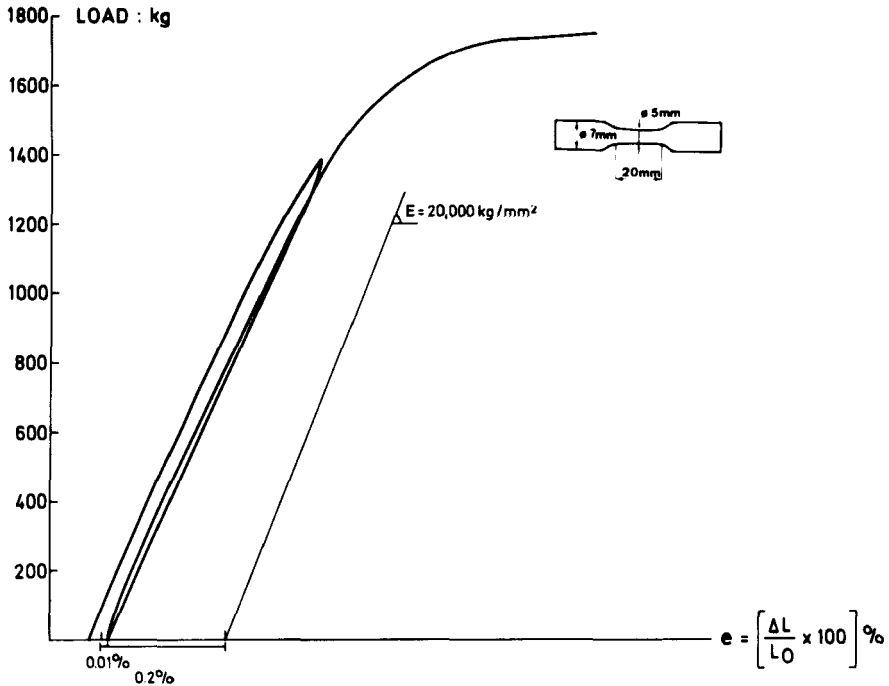


Figure 14 B. A stainless steel specimen taken from a Charnley Prosthesis tested in tension reveals:

- a modulus of elasticity:  $E = 20,000 \text{ kg/mm}^2$ ,
- a  $\sigma_{0.01}$  yield stress:  $\sigma_{0.01} = 68 \text{ kg/mm}^2$ ,
- a  $\sigma_{0.2}$  yield stress:  $\sigma_{0.2} = 87 \text{ kg/mm}^2$ ,
- an ultimate yield stress:  $\sigma_u = 93 \text{ kg/mm}^2$ .

determined on a tensile material specimen taken from the same type of prosthesis (Figure 14).

The 0.01 yield stress was taken as a reference point instead of the 0.2 point which is usually given, because the former is more relevant for a fatigue phenomenon, that is explained by a cyclic loading of the material within a critical zone of stress.

## RESULTS

The relationship of the applied load to the measured strain is shown in Figures 15, 16, 17 and 18. In both types of prosthesis the strain recorded at the lower strain gauge was higher than that at the upper. This is explained by the fact that the lower strain gauge is affected by the clamping of the prosthesis in the epoxy and the difference in cross-

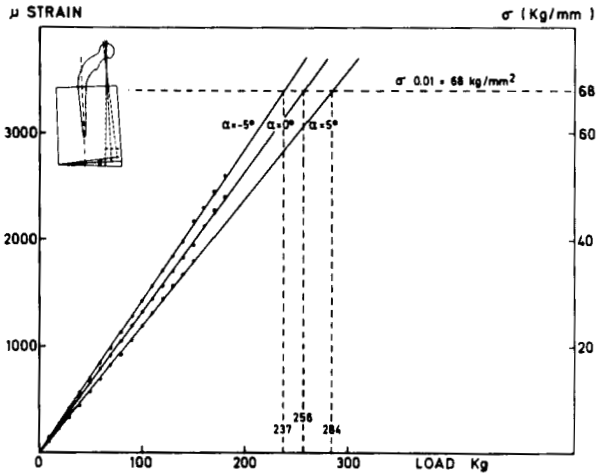


Figure 15. Charnley Prosthesis. Readings at the upper strain gauge.

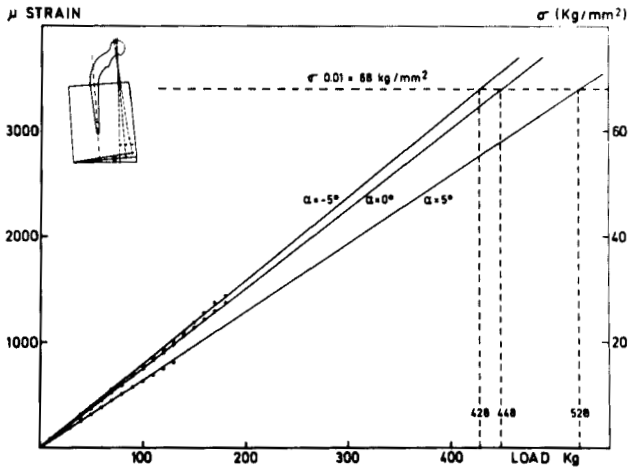


Figure 16. Charnley Prosthesis. Readings at the lower strain gauge.

Figures 15, 16, 17, 18. Load deformation curves for the two types of prosthesis at a loading direction of  $\alpha = 0^\circ$ ,  $\alpha = 5^\circ$  and  $\alpha = (-5^\circ)$ . The strain gauge readings on the left are converted to stress on the right. The loading at the  $\sigma_{0.01}$  level is indicated and taken as a reference point. The actual loading is kept below the yielding point in order to avoid artefacts at reloading by the resultant plastic deformation in the stem or the epoxy. Sufficient strain gauge readings were recorded to allow for an accurate extrapolation of the curve.

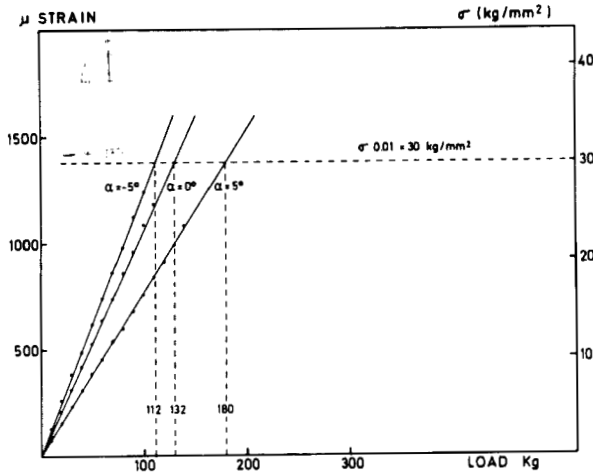


Figure 17. Charnley Muller Prosthesis. Readings at the upper strain gauge.

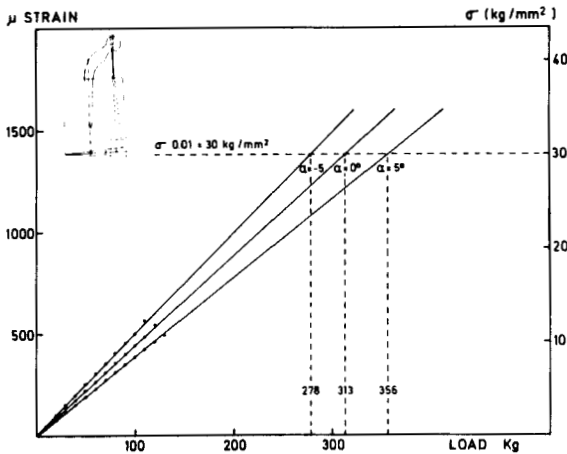


Figure 18. Charnley Muller Prosthesis. Readings at the lower strain gauge.

sectional area at the different levels. The recorded strain at equal loads was higher for the Charnley prosthesis than for Charnley Muller prosthesis.

The moment arm of the bending moment at the femoral stem produced by the loading force at the femoral head was about 25 per cent smaller for the Charnley Muller prosthesis in comparison with the Charnley prosthesis (Figure 12). However, this effect was cancelled to some extent because of the smaller cross-sectional area of the

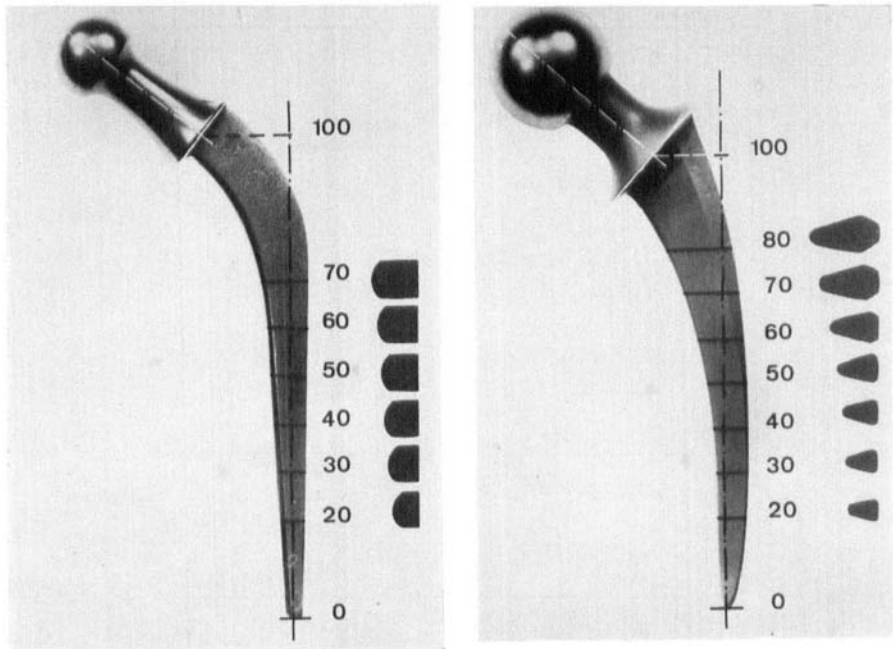


Figure 19. A map of the cross sections of the two types of prosthesis shows the more pronounced tapering of the Charnley Muller type resulting in smaller cross-sectional areas at the levels 60 to 20 per cent stem height.

Charnley Muller femoral stem at the level of the recorded strain. The tapering of the stem is more pronounced in the Charnley Muller prosthesis (Figure 19) resulting in a steeply decreasing cross-sectional area of the stem.

Table 2. Load at the femoral head in kg at which the 0.01 yielding point is reached at the level of the strain gauge for different inclinations of the stem of the two types of prosthesis.

Inclination of the stem	Load at the femoral head for 0.01 yield stress at the lower strain gauge			Load at the femoral head for 0.01 yield stress at the upper strain gauge		
	+5°	0°	-5°	+5°	0°	-5°
Charnley type	284	256	237	528	448	428
Charnley Muller type	180	132	112	356	313	278
Ratio	1.58	1.94	2.12	1.48	1.43	1.54

Figures 15, 16, 17, 18 demonstrate that the 0.01 yield stress was reached at a significantly lower load for the Charnley Muller prosthesis than for the Charnley prosthesis. This difference is mainly due to the different 0.01 yield stress of the material.

The 0.01 yield stress is 68 kg/mm<sup>2</sup> for stainless steel and 30 kg/mm<sup>2</sup> for the Protasul alloy (Figure 14). The absolute values of the load at the yield stress increase from the valgus ( $-5^{\circ}$ ) towards the varus ( $+5^{\circ}$ ) position.

A  $5^{\circ}$  deviation of the prosthesis stem from the femoral shaft axis alters the loading conditions at the femoral stem significantly (Figures 15, 16, 17, 18). There was a  $\pm 20$  per cent decrease of the loading at the femoral head from a  $+5^{\circ}$  position towards a  $-5^{\circ}$  position to obtain the level of 0.01 yielding stress for the surface covered by the strain gauge.

Table 2 shows the load at the femoral head at the 0.01 yielding point for the Charnley and the Charnley Muller prostheses in the different loading directions. The ratio of the loads at the 0.01 yield stress for the two prostheses was approximately 1.5.

#### CONCLUSIONS

In our series of total hip replacements using the Charnley Muller prosthesis (Protasul alloy), a fatigue failure at the femoral stem represented a mechanical complication with a high incidence (6/56). It interfered with the clinical result necessitating a revision in some cases. From the clinical and experimental studies we can conclude that technical, material and mechanical factors are operative in failures of the femoral stem in total hip prostheses.

It would seem to be technically important to insert the stem in the varus position with respect to the femoral shaft axis and to insure that it is well covered by acrylic. The cracking of the acrylic is a potential danger leading to an unfavourable loading condition of the femoral stem. Stainless steel is a more resistant material with regard to fatigue phenomena in comparison with the protasul alloy because of the significantly higher yielding point and its better metallographic structure.

#### SUMMARY

A clinical study of six cases of fracture of the prosthetic femoral stem in Charnley-Muller (Protasul) prostheses has been presented.

Clinical, radiological and metallurgical factors, which may be responsible for these failures, have been discussed. An experimental loading test has been conducted comparing Charnley-Muller and Charnley prostheses at various angles of loading.

The conclusion has been reached that the Charnley stainless steel prosthesis has better fatigue resisting properties than the Charnley-Muller Co, Cr, Mo casting alloy: Protasul, and that the varus position of the femoral stem in relation to the axis of the femoral shaft is of importance in reducing the stresses on the lateral side of the stem.

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