



■ BIOMECHANICS

Biomechanical behaviour of a French femoral component with thin cement mantle

THE 'FRENCH PARADOX' MAY NOT BE A PARADOX AFTER ALL

**Y. Numata,
A. Kaneuji,
L. Kerboull,
E. Takahashi,
T. Ichiseki,
K. Fukui,
J. Tsujioka,
N. Kawahara**

*Kanazawa Medical
University, Ishikawa,
Japan*

- Y. Numata, MD, Graduate student, Department of Orthopaedic Surgery,
- A. Kaneuji, MD, PhD, Professor, Department of Orthopaedic Surgery,
- E. Takahashi, MD, PhD, Associate professor, Department of Orthopaedic Surgery,
- T. Ichiseki, MD, PhD, Clinical professor, Department of Orthopaedic Surgery,
- K. Fukui, MD, PhD, Lecturer, Department of Orthopaedic Surgery,
- J. Tsujioka, MD, Graduate student, Department of Orthopaedic Surgery,
- N. Kawahara, MD, PhD, Professor, Department of Orthopaedic Surgery, Kanazawa Medical University, Ishikawa, Japan
- L. Kerboull, MD, PhD, Editorial Board Member, Marcel Kerboull Institute, Paris, France.

Correspondence should be sent to A. Kaneuji; e-mail: kaneuji@kanazawa-med.ac.jp

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Objective

Cement thickness of at least 2 mm is generally associated with more favorable results for the femoral component in cemented hip arthroplasty. However, French-designed stems have shown favorable outcomes even with thin cement mantle. The biomechanical behaviors of a French stem, Charnley-Marcel-Kerboull (CMK) and cement were researched in this study.

Methods

Six polished CMK stems were implanted into a composite femur, and one million times dynamic loading tests were performed. Stem subsidence and the compressive force at the bone-cement interface were measured. Tantalum ball (ball) migration in the cement was analyzed by micro CT

Results

The cement thickness of 95 % of the proximal and middle region was less than 2.5 mm. A small amount of stem subsidence was observed even with collar contact. The greatest compressive force was observed at the proximal medial region and significant positive correlation was observed between stem subsidence and compressive force. 9 of 11 balls in the medial region moved to the horizontal direction more than that of the perpendicular direction. The amount of ball movement distance in the perpendicular direction was 59 to 83% of the stem subsidence, which was thought to be slip in the cement of the stem. No cement defect and no cement breakage were seen.

Conclusion

Thin cement in CMK stems produced effective hoop stress without excessive stem and cement subsidence. Polished CMK stem may work like force-closed fixation in short-term experiment.

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Keywords: Total hip arthroplasty, French stem, Bone cement

Article focus

- Optimal cement thickness for polished femoral components has not been clearly documented.
- We investigated the effects of reduced cement thickness on Charnley-Marcel-Kerboull stem subsidence and cement movement.

Key messages

- The proximal medial region showed more horizontal than perpendicular migration by tantalum balls in cement.
- The so-called 'French paradox' of excellent survival with thin cement mantles might be explained by the findings of this

study showing that even with a thin mantle, some subsistence still occurred and the thin cement mantle remained intact.

Strengths and limitations

- Strength: we reproduced the environment within the human body (wetness, temperature, continuous dynamic load with unloading 'sleep' periods to provide stress relaxation for the cement).
- Strength: we used precise micro-CT for measurements.
- Limitations: the small number of samples meant that a limited cautious statistical analysis was performed (see supplementary material).

Introduction

In a review of cement fixation systems for total hip arthroplasty (THA), polished surface stems were associated with better outcomes than rough surface stems with a follow up period of more than 20 years.¹ This suggests that a taper slip design with a polished finish stem enables cement creep and are less prone to mechanical failure than rough surface stems.²⁻⁴ Reported outcomes are generally more favourable for cement thicknesses of at least 2 mm, and this thickness is now widely accepted as optimum for the cement mantle.⁵⁻⁷ However, some reports have suggested that French-designed cemented stems are associated with favourable outcomes in the presence of a thin cement mantle.^{8,9}

The French method has always been to maximize stem size within the medullary canal, removing all cancellous bone and fitting the stem in place with cement as filler only where the internal geometry of the bone did not match the implant shape. This approach differs from widely reported research findings that cement stem performance will be poor if the cement mantle is < 2 mm in thickness.

This phenomenon, termed the 'French Paradox', has been discussed in the literature, but the mechanism is not fully understood.⁹ Meanwhile, rough-surfaced stems of French design have been associated with poor outcomes.^{7,9-12} El Masri et al⁹ reported favourable long-term results for polished Charnley-Kerboull stems (Zimmer-Biomet, Warsaw, Indiana) and line-to-line preparation. Most stems did not subside more than 1.5 mm with thin cement thickness. Takahashi et al¹³ performed a biomechanical study using the Collarless Polished Tapered (CPT) stems (Zimmer Biomet, Warsaw, Indiana) with varying thickness of cement mantle, and reported that effective radial creep was associated with a mantle thickness of < 2.5 mm. These reports may suggest that thin cement mantles are acceptable for polished stems. In this study we observed subsidence of the Charnley-Marcel-Kerboull (CMK) (Zimmer Biomet) stems after loading, and we also monitored thin cement behaviour through the movement of tantalum balls within the cement mantle.

Materials and Methods

Loading test equipment. We followed the methodology of Kaneuji et al¹⁴ to create a biomechanical model using cemented femoral components that were inserted into composite femurs (#3403, Pacific Research Laboratories, Vashon, Washington),¹⁵ and performed loading tests. The cancellous bone of this composite femur is much harder than cadaveric bone, and the cement did not penetrate into the cancellous bone. Therefore, using this composite bone enables us to produce a cement mantle of a consistent thickness without a variable infiltration of cement into cancellous bone. The composite femurs were soaked with blended vegetable oil for 24 hours to mimic the wet conditions of the *in vivo* femoral environment.

The composite femurs were attached to a test fixator of S45C structural carbon steel and epoxy resin (Devcon B, ITW Industry, Osaka, Japan).¹³ A metal tube was passed through the composite femur from outside the fixator and fixed precisely at the entry to the medullary canal. A solid rod was passed through this tube to prevent extrusion of cement into the tube at the time of cementing.

Bone cement (Osteobond, Zimmer Biomet) was mixed in a vacuum cement mixing system (ACM vacuum mixing ball, Stryker, Tokyo, Japan), and 80 g of the mixed cement was inserted into the cavity of a composite femur using a cement injection gun after sealing the lower end of the femoral canal with wax. Although a proximal seal was not used for the cement gun, the calcar region was occluded with a finger as the femoral stem was introduced. A double tapered CMK stem No. 302 with < 0.1 μm surface roughness was inserted. We created three models with stem collar in contact with the bone ('contact group') and three models with stem collar positioned 2 mm from the bone ('non-contact group') (Fig. 1). To compare the difference in results by canal preparation, we used a line-to-line technique, with a canal reamer for one stem and a stem broach for two stems in each group. After broaching for the 302 stem, a CMK stem size 302 was used. Because the canal size was thought to fit the size 302 stem, the same size implants were used for all models. For the reaming technique, the canal was reamed to just accommodate a size 302 stem. All CMK stems were considered fixed by line to line preparation.

Before the cement hardened, four or five 0.6mm diameter balls (Bal-tec, MICRO SURFACE ENGR, Los Angeles, California) were inserted into the proximal cement around the stem by indwelling needle (Fig. 2). These balls were used as markers for subsequent micro-CT imaging and cement movement analysis. Balls were also embedded on the tips of the stems for final stem subsidence. To mimic *in vivo* environmental conditions, test equipment was maintained at 37°C by a temperature sensor (T-35; Takigen MFG Co. Ltd., Tokyo, Japan) and a heater (G6A92 [240V, 250W]; Takigen MFG Co. Ltd.).

Loading. Cyclical loading (1 Hz, maximum 3000 N) was applied one million times to a metal femoral head (cobalt-chromium alloy, 26 mm in diameter) attached to the stem. This was estimated to be equivalent to one year of walking.^{16,17} Load was applied using a fatigue testing system (EHF-UM 300KN-70L; Shimadzu Corporation, Kyoto, Japan) at an angle of 15° medially to the coronal plane of the model, to mimic normal *in vivo* loading.¹⁸ An eight-hour non-loading period was provided between the 16-hour loading periods to mimic a sleep period in a clinical setting, and to for allow any stress relaxation. Each loading test lasted 19 days.

Parameters and methods of testing: stem subsidence. A digital displacement gauge (DTH-A5 5 mm; Kyowa Electronic Instruments Co., Tokyo, Japan), placed at the

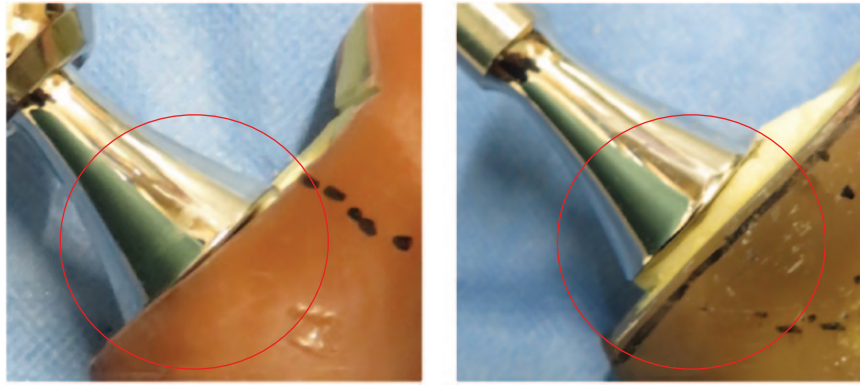


Fig. 1

CMK stem model. A CMK stem was fixed with cement in the composite femur. A model in which the stem collar was brought into contact with the medial bone (Contact group; image on the left side) and a model in which the stem collar was 2 mm away from the medial bone by inserting a 2-mm thick metal board between collar and bone (Non-contact group; image on the right side).

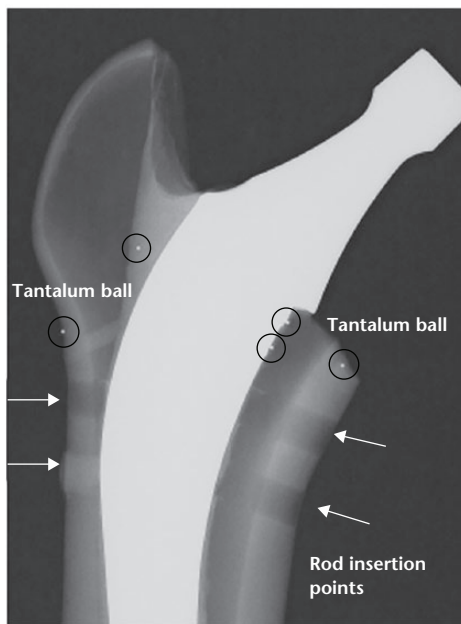


Fig. 2

A radiograph taken after fixing the stem with cement. Tantalum ball fitted to the tip of the tube of indwelling needle was inserted in all areas of proximal femur; medial, lateral, anterior and posterior side before cement hardening, push out with needle, and placed in cement. Four balls were also embedded in the outer circumference of the composite femurs 1 cm proximal to the lesser trochanter. These balls were used as markers for micro computed tomography imaging and cement motion analysis. White arrows indicate the holes for tube.

stem shoulder, was used to measure stem subsidence over time. Data was collected using the method described by Kaneuji et al.¹⁴ The 16-hour loading period for each day was divided into early, middle and late phases and the first two files from each phase (a total of 20 000 values) were collected and used. Data was transmitted automatically to a computer through data collection and analysis software (Sensor Interface PCD-300A; Kyowa Electronic Instruments Co.). Subsidence was defined as the mean of

maximum values for sine waves from the 20 000 values during each phase of the loading period. Perpendicular movement of the tantalum balls at the tips of the stems was measured by micro-CT and was used as the final amount of subsidence. We graphed continuous data on stem subsidence for all models through the experiment.

Parameters and methods of testing: compressive force at the bone-cement interface. A rod in the tube from outside the fixator was connected to a load cell (TR20I 500N/fs, TR20I 200N/fs; Kyowa Electronic Instruments Co.) and the pressure transducer after cement hardening. This rod made contact with the cement at the medullary canal. Compressive force on the cement was measured over time after calibration. The load and no-load periods in a day were classified into three periods (early, middle and late). The compressive force in each period was defined as the mean of the collected 960 maximum values of sine waves in the two consecutive files after the start of each period ($60 \text{ values/min} \times 8 \text{ mins} \times 2 \text{ times}$). A total of 57 averaged values ($3 \times 19 \text{ days}$) were used for analysis of stem subsidence and the compressive force, respectively. The measured values were automatically inputted to a computer. Continuous data of compressive force were graphed throughout the experiment. The relationship between stem subsidence and compressive force at the cement-bone interface were investigated using Pearson's correlation coefficient. A significance level of 1% was used. Statistical analysis was performed using StatView ver. 5.0 (SAS Institute Inc., Cary, North Carolina).

Parameters and methods of testing: tantalum ball movement by micro-CT analysis. Before and after loading, 3D images of the areas within an approximate radius of 2 cm from the markers were obtained using a micro-CT (Microfocus X-ray System CT) scanner (TOSCANER-32250 μ hd; Toshiba IT & Control Systems Corporation, Tokyo, Japan), to measure moving distance and direction of the balls in the cement and at the stem tip. The maximum spatial resolution of the micro-CT scanner was 5 μ m. Images were taken with a

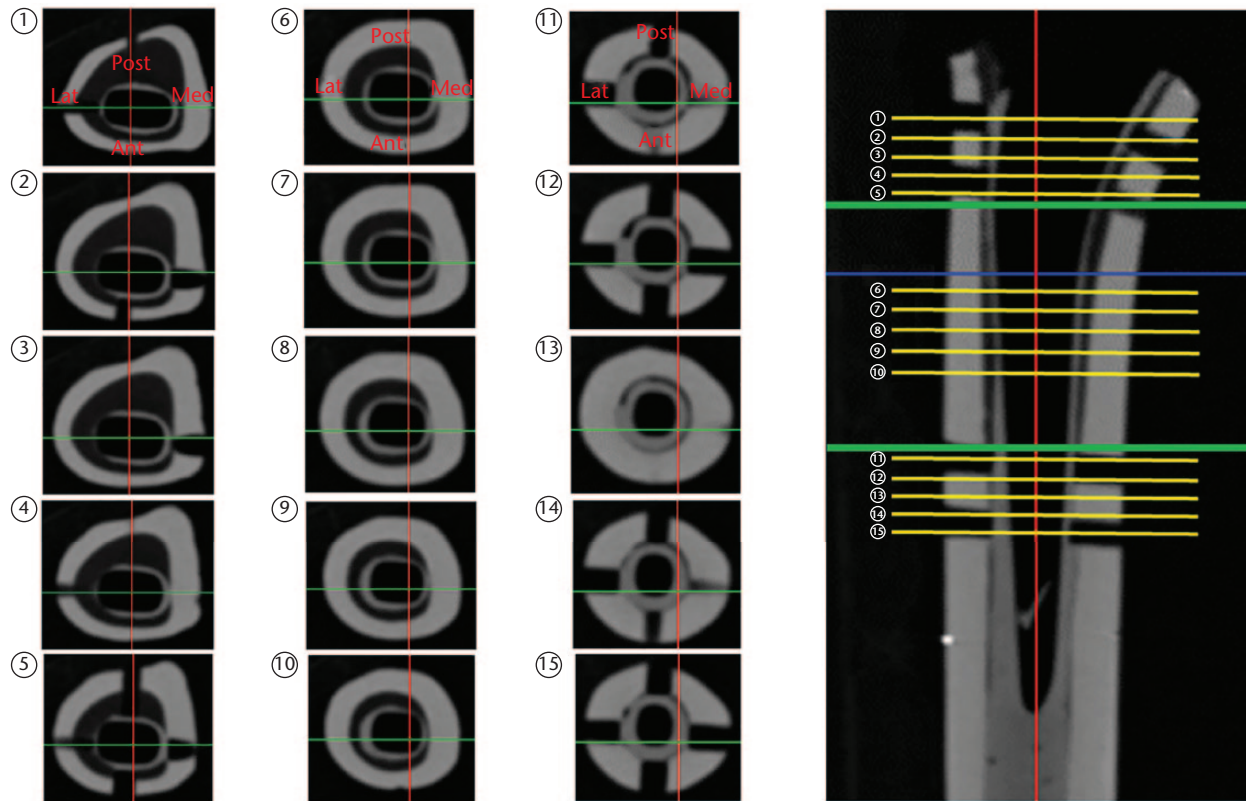


Fig. 3

CT image, taken after removal of stem. Cement thickness was measured for each of five slices in the proximal, middle and distal sections. Each section was defined as follows. The proximal section was from the lower end of the insertion hole for the proximal lateral tube, and the distal section was from the upper end of the insertion hole for the distal lateral tube. The middle section was between the proximal and distal sections. In each section, CT slices were selected for five consecutive slices from the bottom of the proximal section and the top of the distal section. Central five consecutive CT slices were measured in the middle section.

slice spacing of 95 μm . The distance of ball migration was thought to represent the extent of cement movement at a specific location. The position of each ball before applying load was defined as the original point, and the 3D coordinate values after applying load were measured. The magnitude of horizontal and perpendicular migration of the balls was calculated. The values of ball migration distance and the relationships between perpendicular, horizontal and stem subsidence were analyzed.

Parameters and methods of testing: measurement of cement thickness and observation of cement status after stem removal. After completing the loading tests, all stems were removed from the cement. CT images were then taken with a slice spacing of 1 mm to measure the thickness of the cement mantle (Fig. 3).

Using the Gruen zone¹⁹ classification, the proximal section corresponded to zones 1, 7, 8 and 14, the middle section to zones 2, 6, 9 and 13 and the distal section to zone 3, 5, 10 and 12. A total of 360 sites in six femurs (60 sites in one femur \times 15 slices \times 4 sites in each slice) were measured for analysis. A fiberscope camera (Olympus ENF-3; Olympus Corp., Tokyo, Japan) was inserted into the cavity after removing the stem to observe the macroscopic appearance of the cement.

Results

Cement mantle thickness. Since the cancellous bone of this composite bone is hard, only a small interdigitation of cement was observed in all slices of all cases. Although the cement tended to be thicker in the non-contact group, there were no obvious differences in cement thickness between the two groups (Table I). In the observation of four sites per one slice, total 24 sites in the same level slices in six femurs and 120 sites in five slices in each section, mean cement thickness and SD at the proximal, middle and distal section was 1.69 mm SD 0.22, 2.10 mm SD 0.32 and 3.63 mm SD 0.70, respectively. Cement thickness < 2 mm was observed in the proximal, middle and distal sections at 114/120 sites (95%), 65/120 sites (54%) and 2/120 sites (1.7%), respectively.

Cement thickness < 2.5 mm was noted at the proximal, middle and distal sections: 119/120 sites (99%), 108/120 sites (90%) and 9/120 sites (7.5%), respectively.

Mantle thickness was < 3 mm in all cases in the proximal and middle sections, but the distal region had 88/120 sites (73%) of 3 mm or more. The thinnest cement was 1.4 mm at the proximal lateral site and the thickest cement was 5.8 mm at the distal lateral site.

Table 1. Cement thickness was measured as the width on the midpoint of the anterior, posterior, medial and lateral side in each CT slice demonstrated in Figure 3. The values were mean thickness (SD) in each group.

	Contact group				Non-contact group			
	Medial	Lateral	Anterior	Posterior	Medial	Lateral	Anterior	Posterior
① (mm)	1.45 (0.077)	1.4 (0.08)	1.5 (0.09)	1.6 (0.04)	1.68 (0.029)	1.8 (0.141)	1.7 (0.070)	1.85 (0.070)
② (mm)	1.47 (0.082)	1.41 (0.012)	1.58 (0.024)	1.65 (0.04)	1.6 (0.040)	1.6 (0.141)	1.8 (0.122)	1.9 (0.108)
③ (mm)	1.57 (0.09)	1.45 (0.14)	1.55 (0.04)	1.68 (0.03)	1.75 (0.070)	1.65 (0.040)	1.8 (0.081)	1.85 (0.070)
④ (mm)	1.5 (0.04)	1.35 (0.122)	1.65 (0.108)	1.72 (0.043)	1.65 (0.108)	2.0 (0.212)	1.88 (0.216)	2.02 (0.107)
⑤ (mm)	1.64 (0.08)	1.58 (0.113)	1.7 (0.108)	1.78 (0.177)	1.7 (0.040)	2.0 (0.212)	2.0 (0.212)	2.2 (0.318)
⑥ (mm)	1.7 (0.108)	1.8 (0.040)	1.84 (0.234)	1.82 (0.043)	1.88 (0.023)	1.85 (0.108)	2.0 (0.212)	2.1 (0.216)
⑦ (mm)	1.72 (0.043)	2.15 (0.141)	2.02 (0.143)	1.82 (0.28)	1.9 (0.081)	2.3 (0.235)	2.0 (0.362)	2.3 (0.326)
⑧ (mm)	1.85 (0.040)	1.92 (0.307)	2.28 (0.246)	1.92 (0.246)	2.05 (0.103)	2.2 (0.163)	1.85 (0.041)	2.43 (0.017)
⑨ (mm)	2.0 (0.163)	2.1 (0.141)	2.18 (0.028)	2.05 (0.187)	2.3 (0.294)	2.2 (0.283)	2.02 (0.169)	2.5 (0.245)
⑩ (mm)	1.8 (0.374)	2.2 (0.216)	2.75 (0.187)	1.9 (0.108)	2.55 (0.227)	2.4 (0.283)	2.5 (0.081)	2.5 (0.082)
⑪ (mm)	3.5 (0.707)	2.87 (0.094)	2.75 (0.424)	2.2 (0.368)	3.6 (0.454)	3.85 (0.389)	3.6 (0.449)	3.8 (0.355)
⑫ (mm)	3.2 (0.216)	2.48 (0.334)	2.5 (0.408)	2.8 (0.282)	3.8 (0.355)	3.85 (0.389)	4.0 (0.163)	4.1 (0.254)
⑬ (mm)	3.5 (0.245)	3.2 (0.707)	3.1 (0.330)	3.0 (0.0322)	3.8 (0.356)	3.94 (0.178)	4.18 (0.267)	4.16 (0.113)
⑭ (mm)	3.8 (0.424)	3.7 (0.571)	3.5 (0.665)	3.12 (0.322)	4.9 (0.565)	4.05 (0.108)	4.32 (0.216)	4.2 (0.163)
⑮ (mm)	3.4 (0.141)	3.8 (0.424)	3.55 (0.287)	3.15 (0.212)	4.9 (0.141)	4.15 (0.235)	4.45 (0.271)	4.2 (0.163)

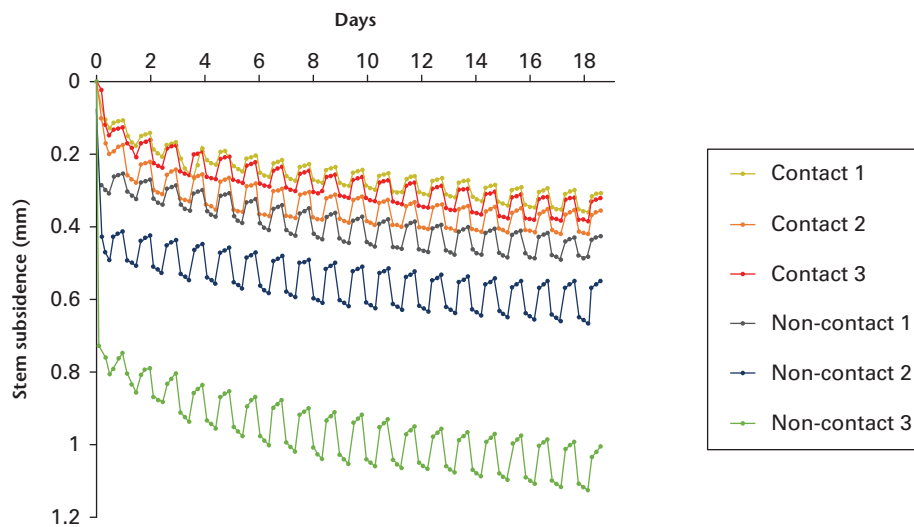


Fig. 4

A graph showing stem subsidence through the experiment. The greatest subsidence occurred on the first day, followed by gradual subsidence thereafter in all models. Contact 1, 2, and 3 showed the data for each contact model, and non-contact 1, 2, and 3 showed the data for each non-contact model.

The amount of stem subsidence. All stems subsided during the loading periods and recovered during the non-loading periods. The greatest subsidence occurred on the first day, followed by gradual subsidence thereafter in all models (Fig. 4). Total mean subsidence (SD) at the end of the experiment was 0.38 mm (SD 0.004) in the contact group and 0.80 mm (SD 0.0063) in the non-contact group, as determined from the ball on the “stem” tip. Slight stem subsidence was observed even in the contact group for one million times load. No obvious difference was observed between the reaming and broaching techniques.

Compressive force at the bone-cement interface. As the investigation proceeded, the compressive force on the bone-cement interface increased in all composite bones in the proximal medial, lateral and distal lateral regions.

However, no great compressive force was noted in other regions (Fig. 5). For all stems, the greatest compressive force was observed in the proximal medial region of the femur (Fig. 6). The compressive force on the final day in both the proximal lateral and the distal lateral regions tended to be greater in the non-contact group than in the contact-group; no difference was seen at the proximal medial region. A strongly significant positive correlation was observed between stem subsidence and compressive force in the proximal medial region in all stems (Fig. 7). No obvious differences were noted in compressive force between the reaming and broaching techniques.

The magnitude and direction of cement migration. We tried to position the balls around the stem on the medial, lateral, anterior and posterior sides but unfortunately, several balls were not optimally placed.

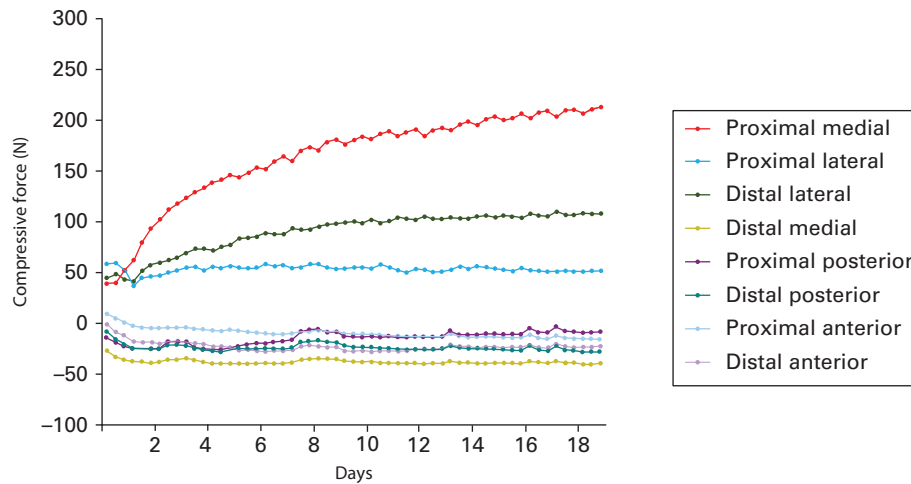


Fig. 5

A graph in continuous observation of the force. This is a graph of a model in the contact group. The compressive forces in medial, lateral, anterior and posterior at proximal and distal side were drawn continuously. Similar graphs were obtained in other models. The force rose with load and slightly fell on unloading period in the course of the day. The greatest force was observed at the proximal medial region in all models.

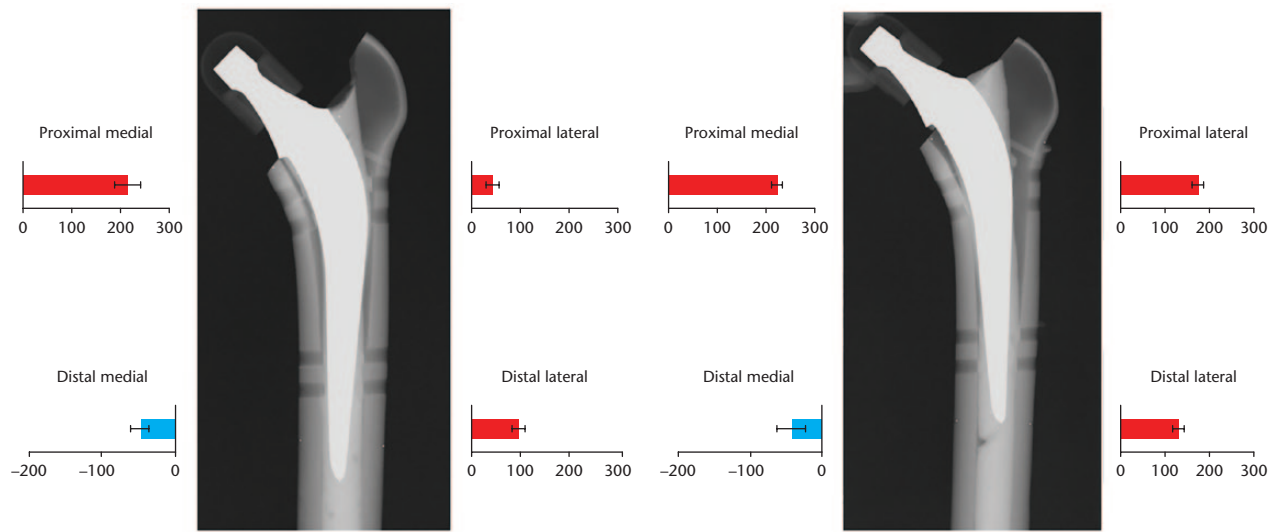


Fig. 6a

Fig. 6b

The final compressive forces at the cement-bone interface for a) the contact group and b) the non-contact group. Major three regions of great compressive force were seen in proximal medial and lateral regions and distal lateral region. Negative small compressive force was seen in distal medial region. The value of bar was mean force in each group, and standard deviation was expressed as a line.

In all models, it was possible to analyze the distance of ball movement in the proximal, medial and lateral regions. For this reason, the ball movement distance was examined only for the balls in the medial and lateral regions and all balls were on the head side of the proximal hole for the tube (Fig. 2). A total of 11 balls were analyzed from the medial region and eight balls from the lateral region (Table II).

All balls migrated in the horizontal direction by at least 0.207 mm and no more than 0.926 mm. Migration in the perpendicular direction was at least 0.197 mm and no more than 0.87 mm. In the proximal medial region, nine of 11 balls moved more in the horizontal direction than the perpendicular direction; this was

attributed to radial creep due to hoop stress. Ball movement distance in the perpendicular direction was 59% to 83% of the stem subsidence. This was attributed to slip in the cement of the stem.

Fiberscope findings after stem removal. No cement defects or cement breakage were noted in any of the femurs when inspected by the fiberscope (Fig. 8), even though the cement mantle was relatively thin.

Discussion

With polished tapered stems, cement creep may result from stem subsidence, and increased compressive force at the bone-cement interface may contribute to stem stabilization^{2,3,13,14,20,21} ('force-closed fixation'^{22,23}).

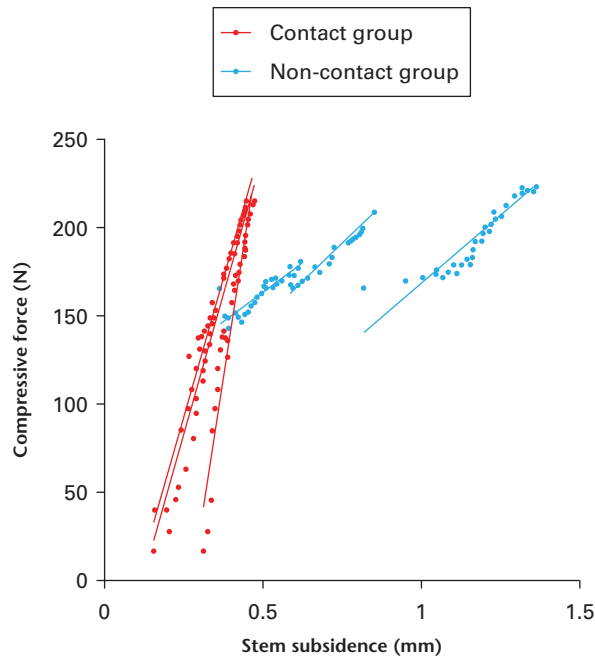


Fig. 7

Correlation of stem subsidence and cement stress in proximal medial region. A significant strong positive correlation by Pearson's correlation coefficient was observed between stem subsidence and compressive force in the proximal medial region in all models. Red lines were the lines of contact group, and blue lines were the lines of non-contact group. A correlation equation, correlation coefficient and p value were following. From left side; $y = 609.68x + 59.443$ $r = 0.802$, $p = 0.007$; $y = 1208.9x + 334.7$ $r = 0.918$, $p = 0.0044$; $y = 641.66x + 78.01$ $r = 0.916$, $p = 0.006$; $y = 129.96x + 98.245$ $r = 0.714$, $p = 0.008$; $y = 170.04x + 62.748$ $r = 0.816$, $p = 0.0073$; $y = 153.34x + 14.994$ $r = 0.778$, $p = 0.0082$.

In France, a thin cement mantle is used to implant a canal-filling femoral component (line-to-line technique). This approach, with excellent long-term results, has been dubbed the 'French paradox'.^{8,9} These stems are supported by the cortex ('shape-closed fixation') as a way to prevent stem subsidence.²⁴

With many varied stem designs in clinical use, the appropriate thickness of the cement mantle for polished surface stems is still under discussion.²⁴

The line-to-line technique press-fits a large stem and applies high compressive force to the cement, resulting in interdigitation into the cancellous bone. This improves the initial fixation of the stem.²⁵

Scheerlinck and Casteleyn²⁴ reported that interdigitation thickened the cement mantle by 3.1 mm on average,

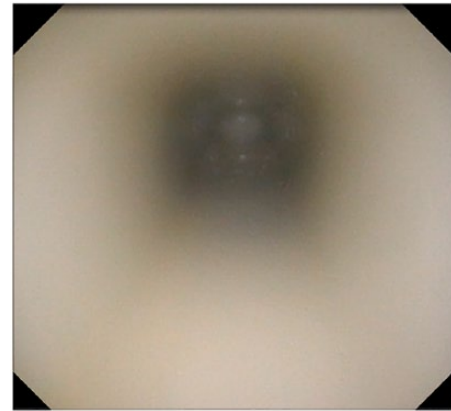


Fig. 8

A fiberscope finding. No cement breakage was noted in any of the models when observed through a fiberscope, even though the cement mantle was relatively thin.

with bone defects in only 6.9% of samples. They concluded that the practical feasibility of a thin cement mantle was uncertain.

We used a composite femur in this study because cadaveric bone, although often used in biomechanical studies, can vary in the curvature of the femur or the quality of cancellous and cortical bone. Composite bone allowed us to achieve the planned cement thickness with the same femoral bowing as in relatively hard cancellous bone without cancellous interdigitation of cement. We could secure the fixation device, accurately measure compressive force and subsidence without risk of femoral fracture, and observe stem and cement behaviour with a relatively thin cement mantle in proximal and middle regions of the femur.

Kärrholm²⁶ reported subsidence with various types of femoral component in a radiostereometric analysis, and El Masri et al⁹ reported that the Charley-Kerboull stem subsided slightly, but not excessively, after canal-filling insertion with a line-to-line preparation. In this study, line-to-line CMK stems also subsided slightly, even in the contact group, but with considerable compression force at the cement-bone interface.

Stem subsidence strongly correlated with compressive force at the proximal medial region in both groups, and may have generated compressive force similar to that for the CPT stem.¹⁴ In addition, the proximal medial region showed perpendicular ball movement less than

Table II. Tantalum balls were migrated in horizontal and perpendicular directions in all models. Horizontal migration of balls was greater than perpendicular migration at the medial region in both groups. No obvious differences were observed between the groups

	Contact group, mean (sd)		Non-contact group, mean (sd)	
	Medial	lateral	Medial	lateral
Horizontal (mm)	0.359 (0.115)	0.219 (0.021)	0.444 (0.216)	0.528 (0.18)
Perpendicular (mm)	0.229 (0.023)	0.281 (0.024)	0.432 (0.198)	0.559 (0.185)
Horizontal/perpendicular migration ratio (%)	155 (0.408)	77.85 (0.048)	102.03 (0.068)	94.12 (0.061)
Ball/stem subsidence ratio (%)	69.06 (0.070)	76.81 (0.189)	74.13 (0.059)	96.89 (0.153)
Stem subsidence (mm)	0.367 (0.075)		0.80 (0.102)	

perpendicular stem movement, and horizontal ball movement greater than perpendicular ball movement. We speculate that stem subsidence in the thin cement mantle led to strong hoop stress and radial cement creep, producing compressive force at the cement-bone interface, especially in the proximal medial region.

Takahashi et al¹³ reported less stem subsidence and associated cement subsidence for CPT stems with a thin cement mantle of < 2.5 mm, and greater likelihood of outward cement creep. In our study, the cement thickness was < 2.5 mm for 95% of all areas in the proximal and middle regions, similar to Takahashi et al's¹³ findings, suggesting that a polished CMK stem might act as a force-closed type stem, at least at the proximal region.

We also investigated differences in mechanical force between the contact and non-contact groups to evaluate the collar effect. Crowninshield et al²⁷ and Tarr et al²⁸ evaluated the level of strain in cemented femoral prostheses, using strain gauges and numerical analysis based on a finite element method. Their results indicated that the collar did not increase transmission of stress to the medial femoral neck. The present study showed similar results in both groups. However, stem subsidence and compressive force in the proximal lateral and distal lateral areas tended to be greater in the non-contact group. These findings suggest that collarless polished stems may be more likely to cause hoop stress due to taper slip than collared stems. Findings for collarless polished taper stems suggest that thin cement mantles may be acceptable if cement surrounds the entire stem for at least a short period.


Within our relatively small number of samples we found no differences between reaming and broaching under line-to-line preparation.

Our study does have some limitations. This was a biomechanical study; results could differ in clinical practice. Although reproducible results were obtained, we only had three models in each group and so we could not conduct a statistical analysis. Loading duration was set to mimic a one-year load in a clinical setting; the results could differ for more extended loading periods. Cement movement was assumed based on the migration of balls within the cement; our simulation may not fully explain actual cement movement. Loading was only applied from one direction, and no real clinical rotation was added; other results may be obtained if rotation is added to the stem. This composite femur did not have cancellous bone in the diaphysis area, resulting in a thick mantle (> 3 mm) in the distal region. Although we took great care to ensure that fixation of the devices for compressive force would not obstruct accurate measurement, we cannot rule out the possibility that our devices affected cement behaviour. The presence of cement defects may lead to different results.

Despite these limitations, our findings were based on measurements obtained under continuous dynamic

load. We hope that they will assist in understanding the dynamics of polished CMK stems with a surrounding thin cement mantle.

Supplementary material

 Figures and a table showing correlation between stem subsidence and cement stress in contact group and non-contact group, and detailed comparison between both groups.

References

1. **Bedard NA, Callaghan JJ, Steff MD, Liu SS.** Systematic review of literature of cemented femoral components: what is the durability at minimum 20 years followup? *Clin Orthop Relat Res* 2015;473:563-571.
2. **Shen G.** Femoral stem fixation. An engineering interpretation of the long-term outcome of Charnley and Exeter stems. *J Bone Joint Surg [Br]* 1998;80-B:754-756.
3. **Lee AJC, Parkins RD, Ling RSM.** Time-dependent properties of polymethylmethacrylate bone cement: the interaction of shape of femoral stems, surface finish and bone cement. In: Older J, ed. *Implant bone interface*. London: Springer-Verlag, 1990:85-90.
4. **Gonzalez Della A, Sharrock N, Barlow M, et al.** The modern, hybrid total hip arthroplasty for primary osteoarthritis at the Hospital for Special Surgery. *Bone Joint Journal [Br]* 1991;73-B:551-558.
5. **Kawate K, Maloney WJ, Bragdon CR, et al.** Importance of a thin cement mantle. Autopsy studies of eight hips. *Clin Orthop Relat Res* 1998;355:70-76.
6. **Mann KA, Gupta S, Race A, et al.** Cement microcracks in thin-mantle regions after in vitro fatigue loading. *J Arthroplasty* 2004;19:605-612.
7. **Jasty M, Maloney WJ, Bragdon CR, et al.** The initiation of failure in cemented femoral components of hip arthroplasties. *J Bone Joint Surg [Br]* 1991;73-B:551-558.
8. **Langlais F, Kerboul M, Sedel L, Ling RS.** The 'French paradox.' *J Bone Joint Surg [Br]* 2003;85-B:17-20.
9. **El Masri F, Kerboul L, Kerboul M, Couppied JP, Hamadouche M.** Is the so-called 'French paradox' a reality?: long-term survival and migration of the Charnley-Kerboul stem cemented line-to-line. *J Bone Joint Surg [Br]* 2010;92:342-348.
10. **Charnley G, Judet T, Pirious P, Garreau de Loubresse C.** Titanium femoral component fixation and experience with a cemented titanium prosthesis. In: Learmonth ID, ed. *Interfaces in total hip arthroplasty*. London: Springer-Verlag, 1993:3-11.
11. **Kerboul L, Hamadouche M, Kerboul M.** Long term result of Charnley-Kerboul total hip replacement in patients younger than 50. In: Caton J, Ferreira A, Picault C, eds. *Arthroplastie totale de hanche*. Lyon: Transit Communications, 2000:37-38.
12. **Hamadouche M, Baqué F, Lefevre N, Kerboul M.** Minimum 10-year survival of Kerboul cemented stems according to surface finish. *Clin Orthop Relat Res* 2008;466:332-339.
13. **Takahashi E, Kaneuji A, Tsuda R, et al.** The influence of cement thickness on stem subsidence and cement creep in a collarless polished tapered stem: when are thick cement mantles detrimental? *Bone Joint Res* 2017;6:351-357.
14. **Kaneuji A, Yamada K, Hirotsaki K, Takano M, Matsumoto T.** Stem subsidence of polished and rough double-taper stems: in vitro mechanical effects on the cement-bone interface. *Acta Orthop* 2009;80:270-276.
15. **Heiner AD.** Structural properties of fourth-generation composite femurs and tibias. *J Biomech* 2008;41:3282-3284.
16. **Crowninshield RD, Brand RA, Johnston RC, Milroy JC.** The effect of femoral stem cross-sectional geometry on cement stresses in total hip reconstruction. *Clin Orthop Relat Res* 1980;146:71-77.
17. **Zahiri CA, Schmalzried TP, Szczechewicz ES, Amstutz HC.** Assessing activity in joint replacement patients. *J Arthroplasty* 1998;13:890-895.
18. **Bergmann G, Graichen F, Rohlmann A.** Hip joint loading during walking and running, measured in two patients. *J Biomech* 1993;26:969-990.
19. **Gruen TA, McNeice GM, Amstutz HC.** "Modes of failure" of cemented stem-type femoral components: a radiographic analysis of loosening. *Clin Orthop Relat Res* 1979;141:17-27.
20. **Fowler JL, Gie GA, Lee AJ, Ling RS.** Experience with the Exeter total hip replacement since 1970. *Orthop Clin North Am* 1988;19:477-489.
21. **Ling RS.** The use of a collar and precoating on cemented femoral stems is unnecessary and detrimental. *Clin Orthop Relat Res* 1992;285:73-83.

22. **Huiskes R, Verdonschot N, Nivbrant B.** Migration, stem shape, and surface finish in cemented total hip arthroplasty. *Clin Orthop Relat Res* 1998;355:103-112.
23. **Shen G.** Femoral stem fixation. An engineering interpretation of the long-term outcome of Charnley and Exeter stems. *J Bone Joint Surg [Br]* 1998;80-B:754-756.
24. **Scheerlinck T, Casteleyn PP.** The design features of cemented femoral hip implants. *J Bone Joint Surg [Br]* 2006;88:1409-1418.
25. **Scott G, Freeman M, Kerboull M.** Femoral components: the French paradox. In: Breusch SJ, Malchau H, eds. *The well-cemented total hip arthroplasty*. Heidelberg: Springer, 2005:249-253.
26. **Kärholm J.** Radiostereometric analysis of early implant migration - a valuable tool to ensure proper introduction of new implants. *Acta Orthop* 2012;83:551-552.
27. **Crowninshield RD, Brand RA, Johnston RC, Pedersen DR.** An analysis of collar function and the use of titanium in femoral prostheses. *Clin Orthop Relat Res* 1981;158:270-277.
28. **Tarr RR, Lewis JL, Jaycox D, et al.** Effect of materials, stem geometry, collar calcar contact on stress distribution in the proximal femur with total hip. *Trans Orthop Res Soc* 1979;4:34.

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Author Contributions

- Y. Numata: Performing biomechanical study, Data analysis, Statistical analysis, Manuscript preparation.
- A. Kaneuji: Study design, Manuscript preparation, Data analysis, Principal investigator.
- L. Kerboull: Performing biomechanical study, Manuscript preparation.
- E. Takahashi: Biomechanical study, Data analysis.
- T. Ichiseki: Manuscript preparation, Data analysis.
- K. Fukui: Manuscript preparation, Data analysis.
- J. Tsujioka: Biomechanical study, Data analysis.
- N. Kawahara: Study design, Manuscript preparation.

Conflict of Interest Statement

- This study was performed using a research grant that was received by our department from Zimmer Biomet Japan KK.

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