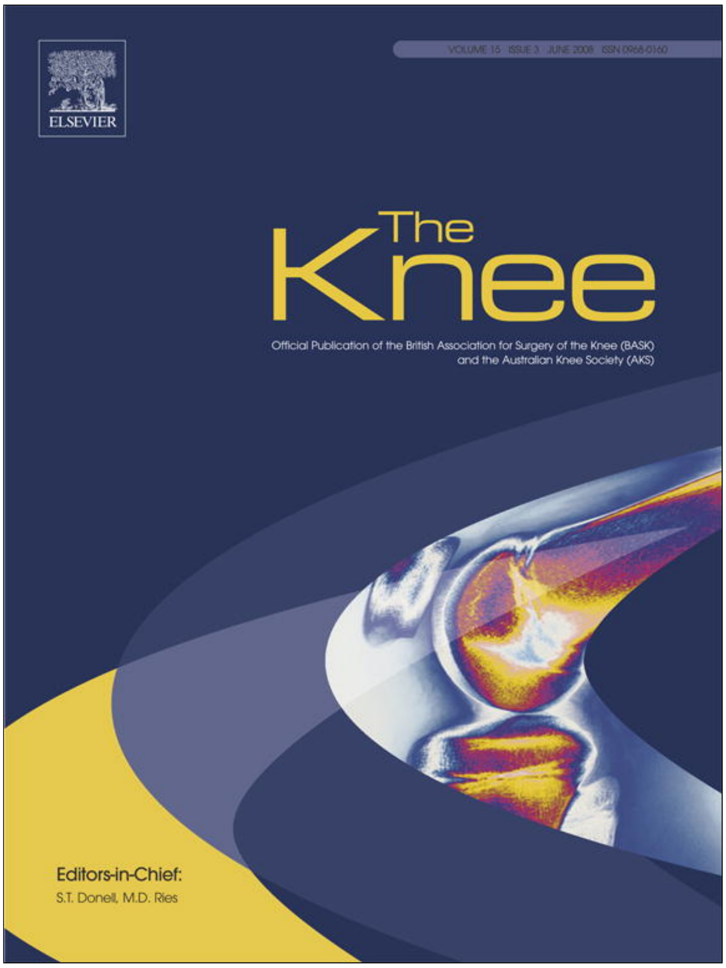
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The influence of different tibial stem designs in load sharing and stability at the cement–bone interface in revision TKA

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Abstract

Total Knee Arthroplasty (TKA) changes mechanical loading of the knee joint. Bone loss in the tibia is commonly encountered at the time of the revision TKA. Restoration of lost bone support and joint stability are the primary challenges in revision TKA. Normally, these defects are treated with non-living structures like metallic augments or bone grafts (autografts or allografts). Alone, neither of these structures can provide the initial support and stability for revision implants. In the latter, the use of intramedullary stems can provide the necessary load sharing and protect the remaining host bone and graft from excessive stress, increasing component stability. The purpose of this study was to evaluate comparatively load sharing (cortical rim, cancellous bone and stem) and stability at the cement–bone interface under the tibial tray induced by the use of cemented and press-fit tibial component stem extensions. Furthermore the study of the desirable option in cases where the bone defect is cavitary (cancellous bone defect contained by an intact cortical rim) or uncontained bone defect (bone loss involving the supporting cortical rim) was carried out. Because *in vitro* evaluation of these biomechanical parameters is difficult we used finite element (FE) models to overcome this. The biomechanical results suggest an identical behaviour in case of cavitary defects for both types of stems assessed. In the case of uncontained defect treated with bulk allografts the cemented stem may be a prudent clinical option.

Keywords: Revision Total Knee Arthroplasty; Load share; Stability; Press-fit stem; Cemented stem; Finite element analysis

1. Introduction

Revision of the Total Knee Arthroplasty (TKA) is often performed in patients with poor bone quality or marked bone loss [1,2], and in these circumstances, stemmed components are helpful to obtain a stable artificial joint construction [3–14]. The restoration of lost bone support and joint stability is the main challenge in revision TKA. The use of bone grafts can achieve this ideal clinical treatment if bone loss associated with revision is cavitary (cancellous bone defect contained by an intact cortical rim) [15–18]. In these situations, the advantages of impacted cancellous bone grafts can be realized [17]. Bulk allograft can be used for larger defects [19,20], mainly to bone loss involving the supporting cortical rim. Alone, neither of these structures can provide the initial support for revision implants. The use of intramedullary stems can provide the necessary load sharing (bypass load) and consequentially off-load the remaining host bone and graft, and simultaneously increase the component stability [10,21]. In general, surgeons nowadays prefer to cement the interfaces of the distal femur and proximal tibia, but it is controversial whether the intramedullary stems should be, cemented or press-fit. The advantages and disadvantages of each type of stem include a number of clinical reasons like surgery technique, limb alignment, end-of-stem pain and facility of remove in re-revision case [6], but there are also biomechanical parameters, like load sharing and stability. Biomechanical data like load sharing and micro-movements at bone–cement interface are difficult to investigate using *in vitro* experiments, nevertheless it becomes a lot easier to analyze when finite element (FE) models are used. From the authors' knowledge, no finite element or *in vitro* studies have been made

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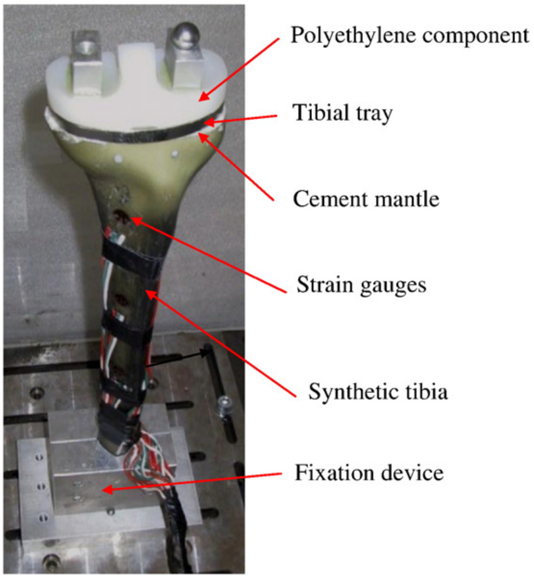

Fig. 1. Implanted synthetic tibia with tri-axial strain gauges.

Table 1
Dimensions of the tibial tray and stems; number of elements and nodes of FE models

Model	PFC Sigma Knee System	Stem	Cement	FE models	
				Elements	Nodes
Standard	Tibial plate — size 5 — Ti-6Al-4 V 83 mm ML — 55 mm AP		CMW 1	257964	47543
Cemented Stem	Tibial plate — size 5 — Ti-6Al-4 V 83 mm ML — 55 mm AP	Æ13 mm × 60 mm Ti-6Al-4V	CMW 1	263450	60825
Press-fit Stem	Tibial plate — size 5 — Ti-6Al-4V 83 mm ML — 55 mm AP	Æ14 mm × 115 mm Ti-6Al-4V	CMW 1	247913	58165

to compare load sharing and stability at the cement–bone interface under tibial tray with the use of cemented or press-fit stems.

The purpose of this study was to evaluate comparatively load sharing (cortical rim, cancellous bone and stem) and stability at the cement–bone interface under the tibial tray induced by the use of cemented and press-fit stem extensions. The analysis also includes the study of the adequate option in cases where bone loss is cavitary treated with impacted cancellous bone or an uncontained defect treated with bulk allograft.

2. Materials and methods

To evaluate comparatively load sharing and stability at the cement–bone interface under tibial tray, models of tibiae identical to the ones used in a previous FE-experimental validation reported study [22] were used. The implants and bone geometries, relative positions between the different structures, materials proprieties and FE 3D meshes are identical to the previous reported study [22]. The FE models of this previous study were able to replicate consistently the mechanical strain behaviour of the proximal tibia reconstructions. A briefly description of this previous FE-experimental validation study is reported. Three synthetic tibiae (3rd generation, left, mod. 3302, from Pacific Research Labs, Vashon Island, WA, USA) were selected and used for the experiments. Triaxial strain gauges (KFG-3-120-D17-11L3M2S, Kyowa Electronic Instruments Co., Ltd., Japan) were glued at the medial-anterior, lateral and posterior side of the cortex at different levels, proximally to the condylar surface (Fig. 1) [22] and were used to measure the surface strains. All strain gauges were connected to a data acquisition system Spider 8 (Hottinger Baldwin Messtechnik GmbH, Germany). Three different tibial components (Fig. 2) of the P.F.C Sigma Modular Knee System (DePuy International, Inc Johnson & Johnson–Warsaw, Indiana, USA) were implanted into synthetic tibiae by an experienced surgeon (Table 1). The three tibial components will be referred in this paper as standard (without stem extension), cemented stem and press-fit stem. CMW-1 (DePuy International, Inc Johnson & Johnson–Warsaw, Indiana, USA) bone cement was used for fixation of the tibial tray to the proximal bone cut and around the cemented stem. The thickness of the cement mantle was kept at 1.5 mm below the tibial tray and 2 mm around the stem, measured from CT scans. Bone strains were measured on all implanted tibiae under simplified loading. The tibia was fixed at the distal region (Fig. 1) through a stiff metal device at 0° adduction [22]. A pneumatic device was used to apply the load (vertical direction) at the medial and lateral condyles independently and at different times [22]. The load was controlled via a load cell (TC4 1T, AEP, Modena, Italy). Each reconstructed tibia was loaded five times. The loading procedure was applied according to Finlay et al. [23]. Two different load cases were applied. Load-case 1 was a vertical force of 1160 N applied on the medial condyle; load-case 2 was a vertical force of 870 N applied on the lateral condyle. These loads correspond to a three times body weight (70 kg) distributed 40% on the lateral condyle (870 N) and 60% on the medial condyle (1160 N) of the

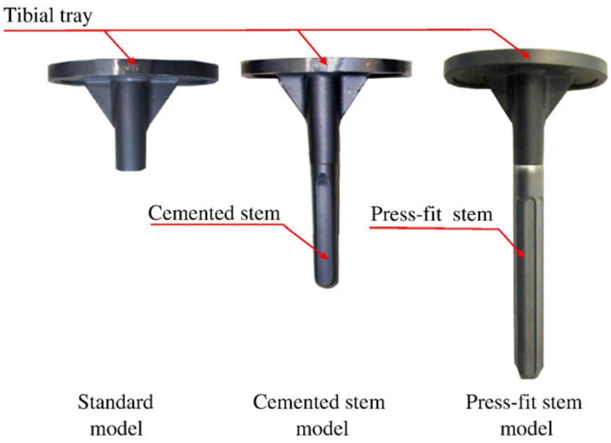

Fig. 2. Models of tibial tray and stem extensions analysed.

Table 2
Materials and their properties used

	Material	Elastic modulus (GPa)	Poisson's ratio
Cancellous bone	Polyurethane foam	0.104	0.3
Cortical bone	Composite material	12.4	0.3
Tibial tray and stems	Titanium	110	0.3
Tibial component	Polyethylene	0.5	0.3
Cement	PMMA	2.28	0.3

Table 3
Forces and moments applied in the FE models

Force/moment	Designation	Value
Axial	(FM)+(FL) (60% medial+40% lateral)	2100 N
Anterior–posterior	AP	220 N
Internal–external moment	IE	7 N m
Patelar ligament	LP	670 N

stance phase before toe-off [24]. The maximal and minimal principal strains within the plane of the gauge were calculated for each gauge location, and standard deviations were determined [22].

To build FE models of implanted tibiae to be used for comparison with experimental models, AP and ML radiographs and CT scans were made onto all *in vitro* reconstructions [22]. The "Standardized Tibia" is a 3D solid model made available in public domain derived from a CT-scan dataset of a synthetic human tibia replica, and was used as the reference geometry for the finite element analysis. The material properties used are those referenced by the manufacturer (Table 2) [25]. The materials are assumed to be homogeneous, isotropic and linear elastic and the boundary conditions of the FE models were defined to reproduce the experimental setup [22]. The tibial components were digitized with a 3-D laser scanner device (Roland LPX 250) and solid models were created with a CAD modelling package (Catia, Dassault Systems, France). The exact position of the tibial tray, cemented and press-fit stems relative to the tibia was determined from CT scans. Automatic meshing of the models was done using FE meshing software HyperMesh v6.0 (Altair Engineering, Troy, Michigan, USA) and meshes were built from 4-node linear tetrahedral, size 1.8 mm. Non-linear analyses were performed with MARC Research Analysis (Palo Alto, CA, USA). The contact between the implant-bone and cement-bone was modelled using the node-to-surface algorithm. In the FE models for validation with experimental ones, the contact between cement mantle and bone cuts was considered glued. The coefficients of friction used were 0.25 [26,27] and 0.3 [28–30] for the contact between implant and cement mantle, and the contact between implant and bone structures (cortical and cancellous), respectively. Coulomb friction model was used in this study.

To investigate load sharing and stability at the bone–cement interface, the same three FE models of the previous study [22] were used, but with changes on the contact proprieties and boundary conditions. A friction coefficient of 1 was considered at the bone–cement interface under the tibial tray. This consideration intends to simulate a mid/long-term clinical scenario, since in this interface it is usually visible radiolucent lines. This condition is the most severe one for revision TKA stability. The friction coefficient value is related to the capacity of the cement to fill the cavities of the cancellous bone and offer great resistance to slip, but at the same time allows interface separation. For these FE models, the load configuration applied on the tibial tray is representative of 45% of the walk cycle on the stance phase before toe-off, obtain by telemetry [31], with patellar ligament force, anterior–posterior forces, axial forces and internal–external moment. The applied loads are summarised in Table 3 and schematically represented in Fig. 3. The stability at cement–bone interface was evaluated by measuring the micro-movements between cement and bone along the medial-lateral alignment (Fig. 4a). This micro-movement is the total displacement of the node of the cement relatively to the node of the bone at the interface plane. Load sharing at the bone–cement interface was assessed by the contact force between the cement mantle and bone (cortical rim and cancellous) in the direction of the mechanical axis of the tibia, and by the load transferred by the stem to the diaphyseal bone. Linear regressions analysis was performed to determine the overall correlation between experimental and numerical strain results [22].

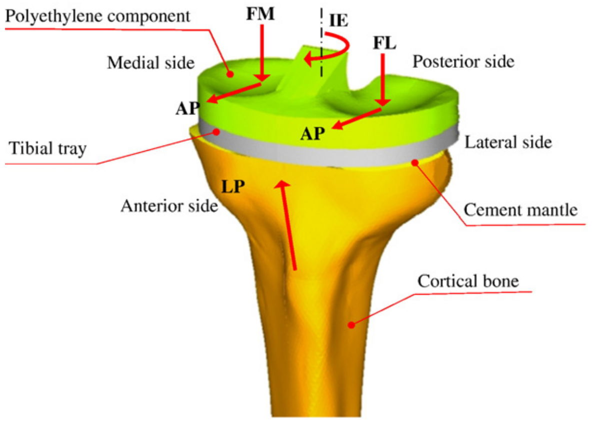

Fig. 3. Schematic representation of applied loads in tibia models.

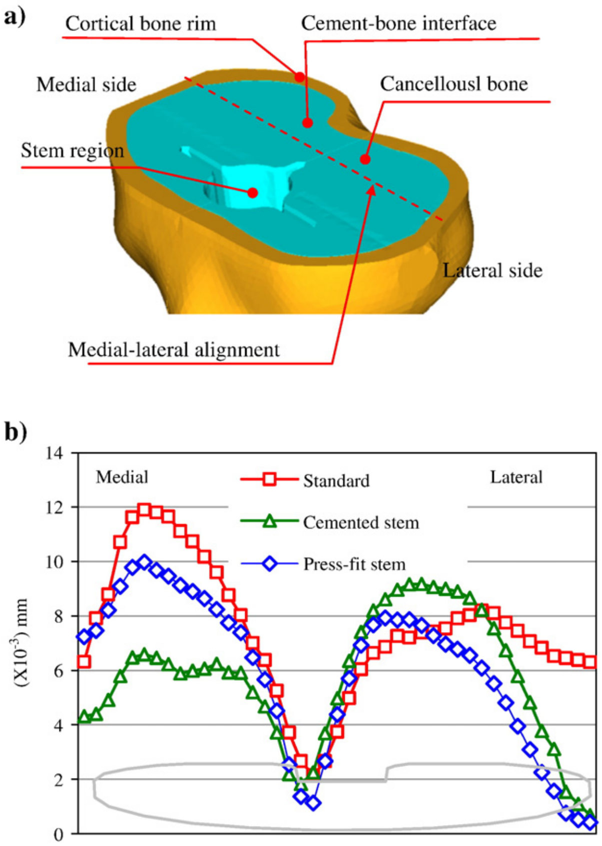

Fig. 4. a) Schematic representation of the medial–lateral alignment, b) Interface micro-movements between cement and bone along the medial–lateral alignment.

3. Results

The standard deviation of the experimental strain data obtained from the five loading runs was less than 5% of the respective mean

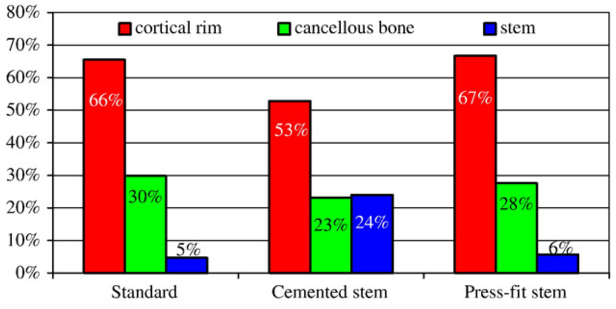

Fig. 5. Load sharing at the cement–bone interface (cortical rim and cancellous) and load transferred by tibial stem analysed.

principal strain. The correlation coefficients between experimental and numerical were within a range of 0.92 and 0.98. The intercept values were within the range of -4.26×10^{-6} m/m and 4.3×10^{-6} m/m and the slope values were within 0.94 and 1.04.

Load sharing at the cement–bone interface (cortical rim and cancellous) as well the load sustained by the stem is presented in Fig. 5. For all models, the cortical rim held the largest axial load transferred by the cement mantle with a maximum of 67% for the press-fit stem and a minimum of 53% for the cemented stem. The cancellous bone sustained 30% for the standard implant, 28% for the press-fit stem and 23% for the cemented stem. The cemented and press-fit stems transferred, respectively, 24% and 6% of the applied axial load to the diaphyseal bone. In the case of the standard implant, the load sustained by the stem (5%) corresponds to the load transferred by the monobloc (50 mm) post of the tibial tray (Fig. 2).

The micro-movements between cement and bone, along the medial-lateral alignment, are presented in Fig. 4b. The highest values were obtained for the standard implant with a maximum of 11.9×10^{-3} mm at the medial side. The lowest values were obtained in the central region (stem region) of the tray. The average of the micro-movements, along the alignment, shows the highest value for the standard implant (7.4×10^{-3} mm). Both implants with stems reduced the average of the micro-movements relatively to the standard one. The press-fit stem reduced 19% and the cemented stem reduced 23%. The peak of reduction was observed at the lateral edge of the tibial tray, with a reduction of 90% of the micro-movement. In the medial edge of the tibial tray, the cemented stem model reduced the micro-movements around 30% relatively to the standard and press-fit stem models.

4. Discussion

This study shows that the use of cemented or press-fit stems at the tibia in revision TKA provokes different capacities of load sharing between cortical rim, cancellous bone and stem at the bone–cement interface with identical stability. The standard deviation of the experimental strain [22] was slightly higher for the mean strains (less than 80×10^{-6} m/m) and is in agreement with the work published by Heiner et al. [32]. For all models, the load transferred to the cortical bone rim was the highest compared to the load transferred to cancellous bone and the load transferred to the distal bone by stem. This is due to the high stiffness of cortical bone with a greater support capacity as well to the tibial tray which “works” like a bridge, where the applied loads on the polyethylene component are shifted to the periphery (cortical bone rim). The stiffness of cortical bone rim plays an important issue in load sharing at the cement–bone interface. The load transferred to cancellous bone is relatively immune to the type of stem (cemented or press-fit); the difference between the two analysed stems was only 5%. The load transferred by the cemented stem to the diaphyseal bone was four times greater than the one transferred by the press-fit stem, as expected, which is the result of the rigid bond between the cemented stem, cement mantle and diaphyseal bone around the stem. The reason for the lowest load transfer capacity of the press-fit stem was due to the consideration, in the FE models, that the contact between stem and bone was made without interference. This consideration is more representative of a clinical mid long-term situation where the possible interference effect as a result of the surgery is reduced due the bone adaptation around the stem. In the mid long term the load carried by the press-fit stem is mainly due to friction forces between the stem and bone. These load sharing results are in agreement with the ones presented by Brooks et al. [33]. These authors found in an experimental study where micro-movements and strains were measured that a tibial stem inserted with cement holds 23% to 38% of the axial load (24% in this study). Also Reilly et al. [34] in an experimental study with strain gauges placed on the cortex found axial load transmitted by cemented metal stems with different lengths. None of these studies evaluated load sharing between the cortical rim and cancellous bone at the cement–bone interface for press-fit or cemented stems.

In what concerns to stability, both types of stems reduced the micro-movements at the bone–cement interface when compared to the ones of the standard implant, an average of 19% for the press-fit stem and 23% for the cemented stem. The increase of stability was especially important in the lateral rim of the tibial tray. Nevertheless, the efficacy of stems extensions has been studied using *in vitro* experiments, [35–37] although conflicting conclusions have resulted concerning improvements in the mechanical stability. Stern et al. [36] found that a long stem increases implant motion. Yoshii et al. [37], using long stems observed a decrease in implant motion. The FE results of this study are in agreement with the parametric study of Jazrawi et al. [35] where it was found that short cemented stems produce tray stability equivalent to the one provided by long press-fit stems. In our study the difference was 4%.

The results of load sharing and stability of this study can be useful to understand the influence of different stems types and allow a better stem selection with the use of impacted cancellous bone grafts or bulk bone allograft to restore bone defects in revision. The treatment of bone loss encountered during revision TKA surgery has different goals. Namely, it makes immediate full weight bearing and achieves a maximum range of motion; it provides a long-term stability for the revision components; and it restores bone stock. The use of bone grafts (autografts or allografts) can achieve this ideal treatment if bone loss is associated with cavitary defects (type 1 bone defect) [15–18,38]. In these situations, the advantages of impacted cancellous bone grafts can be realized. In cases associated with massive bone loss (type 2 or 3 bone defect) [38], multiple surgical options are available, including custom TKA, metal augments and bulk allograft. Structural bulk allografts offer several advantages, including biocompatibility, bone stock restoration, and the potential for ligamentous reattachment [39,40]. Disadvantages of using bulk allografts include late resorption with possible secondary immune reaction [41], fracture or nonunion [39,40], and risk of disease transmission [42,43]. Alone, the use of allografts does not provide the initial support for revision implants. In these cases, the use of intramedullary stems aid to supply the initial support for revision implants providing load sharing [33,34,44] and increase component stability. However an excessive load transferred by stems to diaphyseal bone at the medium long term can be negative due to load-shielding of the allograft and host bone. This can potentially promote bone/allograft resorption and compromise the support of the tibial tray and lead to consequent re-revision. The increase of allograft stability promotes the union with the host bone. Several reports have shown the importance of prolonged rigid fixation to obtain satisfactory union of the allograft to the host bone [39,40].

In defects type 1 [38], limited to the cancellous bone (cavitary defects) treated with impacted cancellous bone, the more important biomechanical parameters for incorporation and longevity of bone graft are the load carry to the cancellous bone and stability at the interface. The differences in this study of load carried to cancellous bone as well as the micro-motions at the cement–bone interface were lower than 5% between stems designs. That suggests identical biomechanical behaviour for both types of stems in case of type 1 bone defect. In this case, the choice of stem can be made with other clinical considerations, like ease removal in case of re-revision (press-fit stem) or flexibility in placement of the implants (cemented stem). In defects type 2 [38], treated with bulk allograft the surgeon tried to restore the cortical rim and cancellous bone in the metaphyseal region. At the allograft incorporation phase the reduction of load carried to the rim of bulk allograft (cortical rim) can be positive due to restricted support capacity of allograft in an early phase. These results make the cemented stem the preferential option in this phase. The cemented stem reduces the load transferred to the cortical rim relatively to the press-fit stem (−14%) and also increases slightly the stability. However, this advantage in the incorporation phase can be negative at long term, with risk of bulk allograft resorption due to a reduction of load stimulus in the bone/allograft. At the long term the press-fit may be the better option. But there are, however, a number of drawbacks in using bone grafts. Bulk allografts of correct size and shape may be difficult to obtain. The attachment of the bulk allograft to host bone is technically demanding. The security of the fixation of these grafts and the success of their incorporation with host bone is dependent upon the quality of alignment with host bone. The long-term fixation and incorporation of bulk allograft is unpredictable, especially if the quality of the host bone is poor or the revision TKA is not optimally aligned and balanced. Thus, these restrictions probably limit the long-term support capacity of the bulk allograft. In these cases, the option for a cemented stem may be prudent. Some clinical results fit with this stem suggestion [8,45–47]. At a final follow-up of 113 revision TKA [45] with 202 metaphyseal-engaging stems, 107 were cemented and 95 were press-fit, 100 (93%) of the 107 implants with cemented stems were stable, seven (7%) were possibly loose, and none were graded as loose. Of the 95 cementless stems, 67 (71%) were categorized as stable, 18 (19%) as possibly loose, and 10 (10%) were loose. In two clinical studies form the same institution [19,20] the results of cemented and cementless stems for type 2 bone defects revealed a higher mechanical failure rate at a much shorter follow-up with the cementless stems compared with cemented stems [46,47]. In 63 cementless stemmed revision TKA, followed for 5.75 years (range, 2–10 years), there were 12 (19%) re-revisions [47]. Combining those revised for aseptic loosening and those with radiographic aseptic loosening, mechanical failure occurred with 10 patients (16%) [47]. In the 38 cemented stemmed revision TKA followed for 10.1 years, 10-year component survival free of revision or removal for any reason was 96.7%; 11-year component survival free of revision for aseptic loosening was 95.7% [46].

The strong point of this FE study was to evaluate the load transferred to the cortical rim, cancellous bone and by stem as well the micro-movements at cement–bone interface with cemented and press-fit stems, through the same tibial tray and bone relative position. The differences between the models are only the stem type preserving all the other parameters like geometry (bone and tibial tray) and material proprieties. For that it is believed that the observed results are representative of the major differences between cemented and press-fit stems. However, this study presents some weaknesses. One limitation is related to the validation of the FE models based solely on the comparison of periosteal bone strains with a low number of tibiae tested. A more effective validation, including a larger number of tibiae models, with other parameters such as: non-linear mechanical behaviour of bone, relative micro-motion between bone and stem and including rotational and transversal loads can also be used for a more reliable FE model validation. Also the results of load sharing and stability in bone–cement interface depend on the alignment and surface coverage of the tibial tray in tibia. Different alignments between tibial tray and bone can provoke different results. It should be also referred that other studies including different implant assemblies may lead to slightly different results.

In conclusion the biomechanical data suggest an identical behaviour in case of cavitary defects for both types of stems assessed. In the case of uncontained defect treated with bulk allografts the cemented stem may be a prudent clinical option.

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