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Strain shielding in proximal tibia of stemmed knee prosthesis: Experimental study

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Abstract

Theoretical concerns about the use of cemented or press-fit stems in revision total knee arthroplasty (TKA) include stress shielding with adverse effects on prosthesis fixation. Revision TKA components are commonly stemmed to protect the limited autogenous bone stock remaining. Revision procedures with the use of stems can place abnormal stresses through even normal bone by their constrained design, type of materials and fixation method and may contribute for bone loss. Experimental quantification of strain shielding in the proximal synthetic tibia following TKA is the main purpose of the present study. In this study, cortical bone strains were measured experimentally with tri-axial strain gauges in synthetic tibias before and after *in vitro* knee surgery. Three tibias were implanted with cemented and press-fit stem augments and solely with a tibial tray (short monobloc stem) of the P.F.C. Sigma Modular Knee System. The difference between principal strains of the implanted and the intact tibia was calculated for each strain gauge position. The results demonstrated a pronounced strain-shielding effect in the proximal level, close to tibial tray with the cemented stem augment. The press-fit stem presented a minor effect of strain shielding but was more extensively throughout the stem. An increase of strains closely to the distal tip of the cemented and the press-fit stem augment was observed. This suggests for a physiological condition, a potential effect of bone resorption at the proximal region for the cemented stem augment. The localized increase of strains in stems tip can be related with the clinical finding of the pain, at the end of stem after revision TKA.

Keywords: Revision total knee arthroplasty; Stress shielding; Tibia; Press-fit stem; Cemented stem; Experimental strains

1. Introduction

Total knee arthroplasty (TKA) alters mechanical loading of the knee joint. Bone surrounding the TKA adjusts its mineral density and structure to meet new mechanical demands. Several studies describe a significant decrease in postoperative bone mineral density (BMD), adjacent to the implant, after TKA (Li and Nilsson, 2000, 2001; Levitz et al., 1995; Lonner et al., 2001; Seitz et al., 1987; Hvid et al., 1988; Petersen et al., 1995; Christ and Hagena, 2000; Bohr and Lund, 1987; Soininvaara et al., 2004). The prosthesis-related bone loss is considered to occur mainly as a result of the phenomena of stress shielding, wear and implant loosening (van Loon et al., 1999). Revision TKA components are commonly stemmed to protect the limited autogenous bone stock remaining. Several studies had analysed the efficacy of stem augments in stability of the tibial component, using *in vitro* experiments (Murray et al., 1994; Bourne and Finlay, 1986; Jazrawi et al., 2001; Stern et al., 1997; Yoshii et al., 1992; Rawlinson et al., 2005), although conflicting conclusions have resulted concerning improvements in the mechanical stability of the implant and potentially harmful effects of stress shielding. Theoretical concerns about the use of cemented or press-fit stems in revision TKA include stress shielding with adverse effects on prosthesis fixation (Murray et al., 1994). For instance, Turner et al. (1997) showed that the average amount of femoral bone loss in a dog model was related

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to stem stiffness and attributed this effect to the greater degree of periprosthetic bone stress shielding engendered by the stiffer stems. A small number of scientific papers (Jazrawi et al., 2001; Finlay et al., 1982; Green et al., 2002; Bourne and Finlay, 1986; Reilly et al., 1982) deal with the measurement of strains on the surface of proximal cadaveric tibia to investigate *in vitro* implant-bone load transfer mechanisms. Bourne and Finlay (1986) demonstrated in a fresh cadaveric strain gauge study the strain shielding between implanted tibia with long press-fit stem and intact tibia. Reilly et al. (1982) measured strains in cadaveric tibia before and after implantation of cemented stems with three different lengths. The variability of mechanical and geometric proprieties of cadaveric bones and tibial tray designs used in these studies limit the comparability of the results of strain shielding between stem types (cemented and press-fit). Commercially available synthetic femur models have been extensively used to evaluate the strain-shielding effect in proximal region. Other studies have shown the adequacy of synthetic tibias to replace cadaveric specimens for certain types of tests (Cristofolini and Viceconti, 2000). Heiner and Brown (2001) showed that the repeatability of these models is superior to those obtained with cadaveric tibia bones.

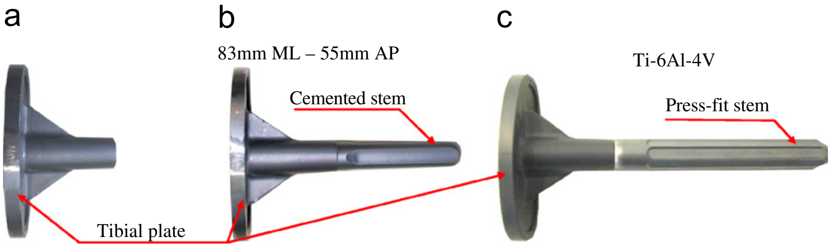
To our knowledge, no experimental strain-shielding studies are available relative to the proximal tibia with synthetic models, before and after TKA. Completo et al. (2007), on a previous experimental-numerical validation study, measured strains in proximal synthetic tibia and compared to those obtained with numerical models, but did not compare strain's changes (strain shielding) before and after implantation in the same tibia model. The goal of the present study was to measure strain shielding in proximal synthetic tibia with three different constructs of TKA. The constructs comprised, respectively, standard stem, cemented stem and press-fit stem. These constructs are the most common ones clinically performed by surgeons in primary or revision TKA. Bone strains were compared with those obtained for the intact tibia to evaluate the level of strain shielding induced by the different design solutions.

2. Materials and methods

In this study, the experimental method described by Completo et al. (2007) was partially used, with exception of the loading procedure. Synthetic tibia bone models were used and strains were measured before and after implantation in the same tibia model. Three synthetic tibias (left, model 3302, from Pacific Research Labs, Vashon Island, WA, USA) were selected and used for the experimental study. Triaxial (rosette) strain gauges (KFG-3-120-D17-11L3M2S, Kyowa Electronic Instruments Co., Ltd., Japan) were glued in intact tibias, before performing the *in vitro* surgeries onto the posterior, antero-medial and lateral side of the cortex at different levels proximally to the condyle surface (Completo et al., 2007). All strain gauges were connected to a data acquisition system Spider 8 (Hottinger Baldwin Messtechnik GmbH, Germany). The positions of the strain gauges were also measured using a 3D coordinate measuring machine (Mod. Maxim, Aberlink, UK) to confirm the same position of the strain gauges between the three models. Three tibial components of the P.F.C Sigma Modular Knee System (DePuy International, Inc., Johnson&Johnson, Warsaw, IN, USA) were implanted into synthetic tibias (Table 1). The tibial component of the prostheses will be referred in this paper as standard stem, cemented stem and press-fit stem. Table 1 gives the description of the stems used in this study. The *in vitro* insertion procedure of the stems was performed according to the clinical protocol. CMW-1 (DePuy International, Inc., Johnson&Johnson) bone cement was used for fixation of tibial tray to the proximal bone cut and around the cemented stem, the thickness of cement mantle was kept at 1.5 mm, below tibial tray and 2 mm around the stem, measured from CT scans. Bone

Table 1
Dimensions and figures of tibial plate (the same in all models) and stems used in the three models

Model	PFC sigma knee system	Stem	Cement
Standard (a)	Tibial plate, size 5, Ti–6Al–4V, 83 mm ML, 55 mm AP		CMW 1
Cemented stem (b)	Tibial plate, size 5, Ti–6Al–4V, 83 mm ML, 55 mm AP	∅ 13 mm × 60 mm Ti–6Al–4V	CMW 1
Press-fit stem (c)	Tibial plate, size 5, Ti–6Al–4V, 83 mm ML, 55 mm AP	∅ 14 mm × 115 mm Ti–6Al–4V	CMW 1



strains were measured on all tibias, before surgery and after surgery (with implant). The tibia was fixed at the distal region (Completo et al., 2007) through a stiff metal device at 0° adduction. A pneumatic device was used to apply the load (vertical direction). The load was controlled via a load cell (TC4 1T, AEP, Modena, Italy) (Completo et al., 2007). As shown in Fig. 1, the load was applied directly on a sphere placed on the customized femoral component to the implanted situation and in a manufactured device to the intact tibia. Each intact and reconstructed tibia replica was loaded five times. The loading procedure was applied according to Finlay et al. (1982). Strains were averaged over these five loading repetitions.

For each reconstruction, the force was applied before surgery in the customized device glued to medial and lateral condyles of intact tibia. The load was applied to the sphere shifted medially in the device. This shifted position relatively to the middle distance between condyles (medial and lateral) allowed a load repartition of 60% to medial condyle and 40% to the lateral condyle (Morrison, 1970). In the implanted situation, the load was transferred to the tibial tray through the customized femoral component and the shifted sphere position in femoral component allows the same load repartition of intact situation. A vertical force of 2030 N was applied in all experiments. This load corresponds 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 stance phase before toe-off (Morrison, 1970).

The maximal and minimal principal strains within the plane of the gauge were calculated for all positions and averaged over the remaining

Fig. 1. Pictures of tibia model before (left) and after surgery (right) with the condylar loading devices.

Table 2
Percentage of changes of the principal strains between implanted and intact tibia (negative values indicate a reduction relatively to the intact principal strains) for the three models at the different strain gauges positions by level and side

	Standard stem			Cemented stem			Press-fit stem		
	P (%)	AM (%)	L (%)	P (%)	AM (%)	L (%)	P (%)	AM (%)	L (%)
ε_1									
Level 0	−65			−58			−81		
Level 1	−31	23	−110	−40	−42	173	−40	−43	−295
Level 2	−20	−4	20	−1	−25	29	−28	−26	15
Level 3	−24	−9	−17	−14	−14	112	2	−19	27
ε_2									
Level 0	9			−64			−28		
Level 1	−18	31	66	−45	−47	−28	−43	−8	63
Level 2	−16	−10	−38	−25	−29	150	−19	−47	−21
Level 3	−13	19	15	−15	−18	14	6	12	117

P: posterior side, AM: antero-medial side, L: lateral side.

reconstructions for each gauge location, and standard deviations were determined. The strain-shielding effect is presented graphically by the absolute difference between principal strains (ε_1, ε_2) in each gauge position of the implanted tibia relative to the intact tibia. The negative values are a reduction relatively to the intact tibia and the positive values an increase. The percentages of the change of the principal strains for all gauge positions are also presented in Table 2.

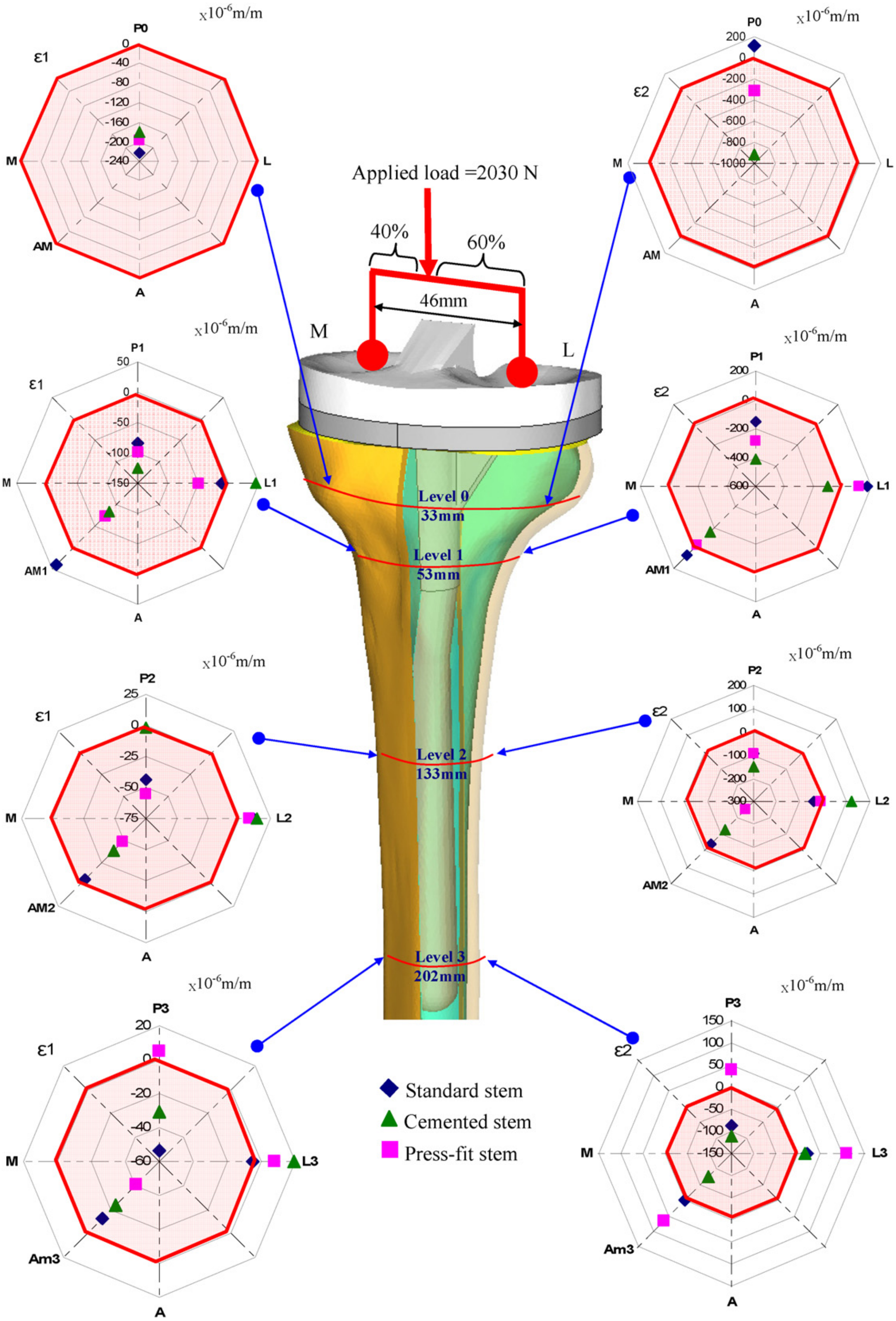


Fig. 2. Differences of principal strains ε_1 (left) and ε_2 (right) between implanted and intact tibia (negative values indicate a reduction relatively to the intact principal strains) at the antero-medial (AM), posterior (P) and lateral (L) sides at four different levels.

3. Results

The standard deviation for the measured strains was smaller than 5.7% of the respective mean principal strain for each gauge position. The differences of the mean principal strains between the implanted and the intact tibia are presented in Fig. 2. The percentages of change for each principal strain relatively to the intact situation are presented in Table 2.

At the level 0, all tibia models reduced the maximal principal (ε_1) strains relatively to the intact situation. The press-fit stem model originated the highest reduction with −81%. At this level, only the stemmed models reduced the minimal principal strains (ε_2) with a maximum nominal reduction for the cemented stem model (-917×10^{-6} m/m, −64%). The standard stem model increased slightly the nominal minimal strains ($+114\times10^{-6}$ m/m, +9%).

At level 1, the reduction of nominal minimal and maximal principal strains occurred for the generality of all strain gauge positions and models. The biggest nominal reduction occurred in the posterior side to the cemented stem tibia for the minimal principal strains (-408×10^{-6} m/m). For the maximal principal strains, the greatest nominal reduction occurred in the posterior side for the cemented stem (-125×10^{-6} m/m). An increase of nominal minimal principal strains in lateral side occurred for the standard ($+174\times10^{-6}$ m/m) and press-fit stem ($+116\times10^{-6}$ m/m). Also occurred an increase of nominal maximal principal strains in lateral side ($+49\times10^{-6}$ m/m) for the cemented stem and in antero-medial side ($+48\times10^{-6}$ m/m) for the standard stem.

At level 2, the stemmed models had the tendency to reduce the minimal and maximal principal strains in the posterior and antero-medial sides. The greatest nominal reduction occurred for the minimal principal strains and for the press-fit stem in the antero-medial side (-252×10^{-6} m/m). In the lateral side, the tendency was to augment or maintain the nominal principal strains. The cemented stem model increased ($+123\times10^{-6}$ m/m) the minimal principal strain (+150%).

At level 3, the standard and cemented stem models tended to maintain or reduce both nominal principal strains. The tendency of the press-fit stem model was to increase the nominal minimal principal strains. The maximum increase occurred in the lateral side with $+107\times10^{-6}$ m/m, which represents more than 117% relative to the intact situation.

4. Discussion

The purpose of this study was to evaluate experimentally strain shielding in the proximal tibia with three different constructs of TKA, by comparing cortical strains between the implanted and intact tibia.

The results show that the minimal principal strains were generally higher for the strain gauges localized on the antero-medial side and the maximum principal strains were higher on the lateral side. In fact, the load applied generates essential compression deformations on the medial side and tension ones on the lateral side, due to the bending moments generated by the medial shifted load. The load repartition on the tibia is representative of physiological loading of the knee in the stance phase. The absolute values of minimal principal strains were higher than the absolute values of maximal principal strains for most of the strain gauges. Due to this fact, special attention was given to the changes of the minimal principal strains between the intact and the implanted tibias. With some exceptions, all minimal and maximal principal strains were reduced relatively to the ones of the intact tibias, inducing strain shielding.

The strains differences between the implanted and the intact tibia by level showed the highest reductions at the proximal levels (0 and 1). These reductions were particularly important for the stemmed tibias. The cemented stem tibia showed a reduction of minimal principal strains three times higher than the press-fit stem tibia and four times higher than the standard stem tibia at the P0 position. The standard stem model increased the minimal principal strains at level 0 and level 1 in lateral and antero-medial side. These results at the proximal levels demonstrate a strong effect of strain shielding for the cemented stem with potential effect of bone resorption in a physiological environment. This can be explained by the load transfer capacity of the cemented stem to the distal region. The press-fit stem generated a minor effect of strain shielding at these levels, a behaviour between the standard and cemented stem models. These results for the press-fit stem tibia suggest a reduced effect of load transfer by the press-fit stem. The standard stem tibia evidenced a tendency for maintaining or increasing the strains, which can promote a physiological bone remodelling process or fatigue damage if the increases of strains exceed the fatigue strength of the host bone.

At the distal level (levels 2 and 3), the average changes in maximal principal strains for all models were inferior to 50×10^{-6} m/m. For the minimal principal strains, the main reduction was for level 2 at the antero-medial position for the press-fit stem model; the largest augment was at the lateral side for the cemented stem. At level 3, the press-fit stem model increased the minimal strains in all tibia sides, with the main increase in the lateral side. At the posterior side, strains reductions were observed for the standard and cemented stem. The results at the distal levels demonstrate a minor effect of strain shielding comparatively to the proximal levels for all models. This effect was more pronounced at level 2 for the press-fit stem model. At this level, this effect was not due to the load transfer mechanism by the press-fit stem, but due to the bending moment generated in condylar surface which was partially supported by the press-fit stem, and therefore reduced the bending moment through the bone along the stem length, reducing consequently the bone strains when compared with intact bone strains. The main increase of the minimal principal strains was at the lateral side at level 2 for the cemented stem and at level 3 for the press-fit stem and can be related with the tip stem fulcrum effect on the bone. Due to the bending moment generated in the condylar surface, the force moment pushes the tip of stems again the bone and provokes strain concentration around the tip region.

It seems that only few experimental studies with strain gauges are available relative to the analysis of the proximal tibia before and after TKA with use of stems. Completo et al. (2007), on a previous experimental-numerical validation study, measured strains in synthetic tibia and compared to those obtained with numerical models, but did not compare strains changes (strain shielding) before and after the implantation of stems in the same tibia model. No more than two experimental strain gauges studies of Bourne and Finlay (1986) and Reilly et al. (1982) compared proximal strains before and after TKA with use of stems in the same cadaver specimen. The cadaveric study of Bourne and Finlay (1986) shows an effect of strain shielding with the use of press-fit stems (short and long) in the medial and lateral sides, which are in line with our results. However, our study has demonstrated a more important effect of strain shielding in the posterior side for the long press-fit stem than at the lateral or anterior-medial side. We cannot compare this result with the study of Bourne and Finlay (1986) because their study does not present the results at the posterior side. Like Bourne and Finlay (1986) study, our standard stem model equivalent to 3.75 cm stem of their study demonstrated low strain-shielding effect. The strains increase in the lateral side at distal level for the long press-fit stem presented by Bourne and Finlay (1986) is also present in our study. The cadaveric study of Reilly et al. (1982) showed also an effect of strain shielding in the proximal tibial with the use of short-cemented stems. Their results of strain shielding in the posterior side were inferior when compared with ours at the proximal levels. One explanation for these differences can be our tibial tray design. Our tibial tray design is characterized by "U" shape in the posterior side for PCL (posterior crucicate ligament) conservation. This geometry reduces the contact between the tibial tray and the cortical rim of the implanted tibia and consequently the load carry to posterior cortical bone (Bourne and Finlay, 1986).

The two studies of Reilly et al. (1982) and Bourne and Finlay (1986) have used different stem types, tibial trays, cadaver specimens, strain gauge positions and applied loads. All these differences make the comparability of results of strain shielding between stem types difficult. The advantage of the present study is in the comparison of the strain-shielding effect for two different stem types (cemented and press-fit) with the same model conditions. Our results demonstrate at the proximal levels (1 and 2) a more pronounced effect of strain shielding for the cemented stem when compared with the press-fit stem. This may be due to the load sharing capacity of the cemented stem (Reilly et al., 1982). The press-fit stem had a minor effect of strain shielding but was more extensive along all length of the stem. The strain shielding in the press-fit stem does not have the same cause of the cemented stem. The press-fit stem does not have a great load sharing capacity because this stem is only in contact with friction with bone without interference (diameter of stem = diameter of reamed bone). This effect is due to the bending moment generated in the condylar surfaces which is partially supported by the press-fit stem, which originates a reduction of the bending moment through the bone along the stem length, reducing bone strains.

Based on the results obtained within this experimental study and extrapolating these for a physiological condition, these can promote bone resorption effect on the proximal level for the cemented stem, higher than that for the press-fit stem. The strain concentration effect at the stem tip of the cemented and press-fit stem is an additional concern due the stem fulcrum effect in the bone. Due to the bending moment generated in the condylar surface, this moment pushes the tip of stem against the bone and originates strain concentrations at tip region. This effect may be the cause for pain at the distal end of the stem after revision TKA (Barrack et al., 1999, 2004; Haas et al., 1995). Barrack et al. (1999) reported 14% of patients with localized pain in tibia with press-fit stems. This augment of strain can induce also hypertrophy of the cortical bone at this region (Bertin et al., 1985; Peters et al., 2005).

It would be interesting to obtain strains more proximally, near the condyles region, but it was technically difficult to place strain rosettes in this region of the tibia without damaging them when performing the *in vitro* surgeries to implant the prosthesis. The alternative to obtain strains more proximally, near the condyles region, would be to replace the used jig cutting system of the implant supplier (Depuy) by manufacturing a dedicated jig system, in order that bone cuts can be made leaving the proximal region of the tibia free of supports and guides (a prospect for a future work).

Other limitation of this study is related to the loads applied on the synthetic tibias. In this study, only axial loads were applied without the anterior–posterior and patella forces and the internal–external moment. Even so, due to the comparative nature of the study, the results are representative of major differences between the models analysed.

Conflict of interest

It is confirmed that all authors have seen and agreed with the contents of the manuscript and confirm that the work has not been submitted or published elsewhere.

Also all authors confirm that they do not have any financial and personal relationships with other people or organizations that could inappropriately influence this work.

References

Barrack, R.L., Rorabeck, C., Burt, M., Sawhney, J., 1999. Pain at the end of the stem after revision total knee arthroplasty. Clinical Orthopaedics and Related Research 367, 216–225.

Barrack, R.L., Stanley, T., Burt, M., Hopkins, S., 2004. The effect of stem design on end-of-stem pain in revision total knee arthroplasty. The Journal of Arthroplasty 19, 119–124.

Bertin, K.C., Freeman, M.A.R., Samuelson, K.M., Ratcliffe, S.S., Todd, R.C., 1985. Stemmed revision arthroplasty for aseptic loosening of total knee replacement. The Journal of Bone and Joint Surgery—British volume 67, 242–248.

Bohr, H.H., Lund, B., 1987. Bone mineral density of the proximal tibia following uncemented arthroplasty. The Journal of Arthroplasty 2, 309–312.

Bourne, R.B., Finlay, J.B., 1986. The influence of tibial component intramedullary stems and implant-cortex contact on the strain distribution of the proximal tibial following total knee arthroplasty. Clinical Orthopaedics and Related Research 208, 95–99.

Christ, R.M., Hagena, F.W., 2000. Bone mineral density after total knee arthroplasty considering the influence of diphosphonates in osteoarthritis and rheumatoid patients. Presented at the 67th Annual Meeting of the American Academy of Orthopaedic Surgeons, Orlando, FL.

Completo, A., Fonseca, F., Simões, J.A., 2007. Finite element and experimental cortex strains of the intact and implanted tibia. Journal of Biomechanical Engineering 129 (5), 791–797.

Cristofolini, L., Viceconti, M., 2000. Mechanical validation of whole bone composite tibia models. Journal of Biomechanics 33, 279–288.

Finlay, J.B., Bourne, R.B., McLeant, J., 1982. A technique for *in vitro* measurement of principal strains in the human femur. Journal of Biomechanics 15, 723–739.

Green, G.V., Berend, K.R., Berend, M.E., Glisson, R.R., Vail, T.P., 2002. The effects of varus tibial alignment on proximal tibial surface strain in total knee arthroplasty. The Journal of Arthroplasty 17, 1033–1039.

Haas, S.B., Insall, J.N., Montgomery, W., Windsor, R.E., 1995. Revision total knee arthroplasty with use of modular components with stems inserted without cement. The Journal of Bone and Joint Surgery—American volume 77, 1700–1707.

Heiner, A.D., Brown, T.D., 2001. Structural properties of new design of composite replicate femurs and tibias. Journal of Biomechanics 34, 773–781.

Hvid, I., Bentzen, S.M., Jorgensen, J., 1988. Remodeling of the tibial plateau after knee replacement: CT bone densitometry. Acta Orthopaedica Scandinavica 59, 567–573.

Jazrawi, L.M., Bai, B., Kummer, F.J., Hiebert, R., Stuchin, S.A., 2001. The effect of stem modularity and mode of fixation on tibial component stability in revision total knee arthroplasty. The Journal of Arthroplasty 16, 759–767.

Levitz, C.L., Lotke, P.A., Karp, J.S., 1995. Long-term changes in bone mineral density following total knee replacement. Clinical Orthopaedics and Related Research 321, 68–72.

Li, M.G., Nilsson, K.G., 2000. Changes in bone mineral density at the proximal tibia after total knee arthroplasty. Journal of Orthopaedic Research 18, 40–47.

Li, M.G., Nilsson, K.G., 2001. No relationship between postoperative changes in bone density at the proximal tibia and the migration of the tibial component 2 years after TKR. The Journal of Arthroplasty 16, 893–900.

Lonner, J.H., Klotz, M., Levitz, C., Lotke, P.A., 2001. Changes in bone density after cemented total knee arthroplasty, influence of stem design. The Journal of Arthroplasty 16, 107–111.

Morrison, J.B., 1970. The mechanics of the knee joint in relation to normal walking. Journal of Biomechanics 3, 51–61.

Murray, P.B., Rand, J.A., Hanssen, A.D., 1994. Cemented long-stem revision total knee arthroplasty. Clinical Orthopaedics and Related Research 309, 116–123.

Peters, C.L., Erickson, J., Kloepper, R.G., Mohr, R.A., 2005. Revision total knee arthroplasty with modular components inserted with metaphyseal cement and stems without cement. The Journal of Arthroplasty 20, 302–308.

Petersen, M.M., Nielsen, P.T., Lauritzen, J.B., Lund, B., 1995. Changes in bone mineral density of the proximal tibia after uncemented total knee arthroplasty: a 3-year follow-up of 25 knees. Acta Orthopaedica Scandinavica 66, 513–516.

Rawlinson, J.J., Peters, L.E., Campbell, D.A., Windsor, R., Wright, T., Bartel, D., 2005. Cancellous bone strains indicate efficacy of stem augmentation in constrained condylar knees. Clinical Orthopaedics and Related Research 400, 107–116.

Reilly, D., Walker, P.S., Ben-Dov, M., Ewald, F.C., 1982. Effects of tibial components on load transfer in the upper tibia. Clinical Orthopaedics and Related Research 165, 273–282.

Seitz, P., Ruegsegger, P., Gschwend, N., Dubs, L., 1987. Changes in local bone density after knee arthroplasty. The Journal of Bone and Joint Surgery—British volume 69, 407–411.

Soininvaara, T.A., Miettinen, H.J.A., Jurvelin, J.S., Suomalainen, O.T., Alhava, E.M., Kröger, H.P.J., 2004. Periprosthetic tibial bone mineral density changes after total knee arthroplastyOne-year follow-up study of 69 patients. Acta Orthopaedica Scandinavica 75, 600–605.

Stern, S.H., Wills, R.D., Gilbert, J.L., 1997. The effect of tibial stem design on component micromotion in knee arthroplasty. Clinical Orthopaedics and Related Research 345, 44–52.

Turner, T.M., Sumner, D.R., Urban, R.M., Igloria, R., Galante, J.O., 1997. Maintenance of proximal cortical bone with use of a less stiff femoral component in hemiarthroplasty of the hip without cement. An investigation in a canine model at six months and two years. The Journal of Bone and Joint Surgery—American volume 79, 1381–1390.

van Loon, C.J., Waal, M.C., Buma, P., Verdonschot, N., Veth, R.P., 1999. Femoral bone loss in total knee arthroplasty. A review. Acta Orthopaedica Belgica 65, 154–163.

Yoshii, I., Whiteside, L.A., Milliano, M.T., White, S.E., 1992. The effect of central stem and stem length on micromovement of the tibial tray. The Journal of Arthroplasty 7, 433–438.