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Analysis of an early intervention distal femoral resurfacing implant for medial osteoarthritis

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ABSTRACT

A design concept was formulated for implants to treat medial osteoarthritis of the knee, using a metal plate resurfacing of the tibia plateau and a plastic bearing embedded in the distal end of the femur. A finite element analysis was carried out to determine whether a metal backing would be needed for the femoral component, and to what extent the stress and strain distribution in the trabecular bone surrounding the implant would match the normal intact condition. The CT scans from three knees scheduled for unicompartmental replacement were selected to generate computer models with variable bone densities in each element to cover a range of density patterns. Loading conditions were defined for a range of flexion angles, from loads at the center to the end of the component. A 2-peg fixation design was analyzed for both an all-plastic and a metal-backed construction. For the metal-backed, the interface von Mises stresses were close to intact values at the same level in the bone, although there was a 34 percent increase for loading at the end of the component. However, the all-plastic gave stresses elevated up to 109 percent. The maximum principal strain values for metal-backed in the trabecular bone below the implant were variable between specimens but close to intact under all conditions. In contrast the all-plastic showed strains up to 81 percent increased. The metal pegs showed load transfer, but the loads transmitted by the plastic pegs was small, as evidenced by the low interface stresses. The conclusion was that metal-backing was necessary to avoid excessive bone stresses and strains, while metal peg fixation was evidently an advantage.

1. Introduction

Unicompartmental knee replacement is a well-established option for the treatment of medial osteoarthritis. In an extensive review of design and surgical techniques, the various factors leading to successful results were identified as well as the failure modes and their causes (Maduekwe et al., 2010). It was concluded that results have steadily improved over time due to a number of factors. Failures due to wear have reduced substantially due to the use of mobile bearings and by highly wear-resistant polyethylene. Instability has been reduced and kinematics improved by more accurate surgery, especially when robotic techniques have been used (Watanabe et al., 2014). Reproduction of the anatomic sagittal profile of the femur can be inaccurate however, especially using conventional techniques. Tibial loosening is still an important problem, however, this is most likely due to the substantial depth of tibial plateau resection to accommodate the component thickness. The consequence is the removal of the strongest bone near the surface of the tibial plateau (Goldstein et al., 1983; Hvid and Hansen, 1985). Furthermore the strength of the bone itself diminishes with age (Ding et al., 1997).

To address these limitations, a new 'reversed materials' type of uni replacement was proposed, where the tibial component consisted of a metal plate of thickness 3–4 mm, and the femoral component was a polyethylene bearing with a metal backing of 9 mm total thickness inset into the distal end of the femur (Chaudhary and Walker, 2014). This was termed an Early Intervention (EI) design. The justification for the femoral configuration was that the most common femoral osteoarthritic lesions on the medial femoral condyle occur in that region (Arno et al., 2011, 2012; Bae et al., 2010). Furthermore, this area is most frequently subjected to load-bearing in walking and other low-flexion activities. It is noted that the femur now requires a greater bone resection depth. However the bone density does not reduce as rapidly below the surface as in the tibia, and if a revision to a total knee is needed in the future, 9–10 mm distal femoral resection is required.

A device utilizing 'reverse materials', the Load Angle Inlay, was first introduced by Charnley in the early 1970s. In a report of 24

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early failures, problems due to polyethylene wear and deformation, and some case of tibial component loosening, were described (Minns and Hardinge, 1983). The only clinical follow-up report, of 747 cases at 20–28 years follow-up, was in the form of a conference lecture (obtained as a personal communication by the second author, Purbach 2004). It was stated that overall the design was successful, with failures occurring primarily due to misalignment. From the above studies, it appeared that the main causes of failure could be addressed with improvements in design, indications, techniques, and materials. In this study, we address femoral component design.

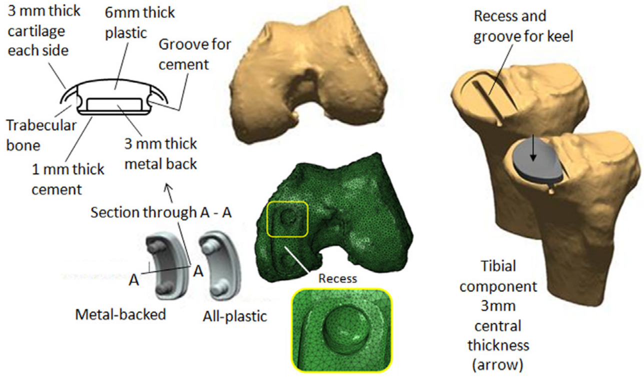


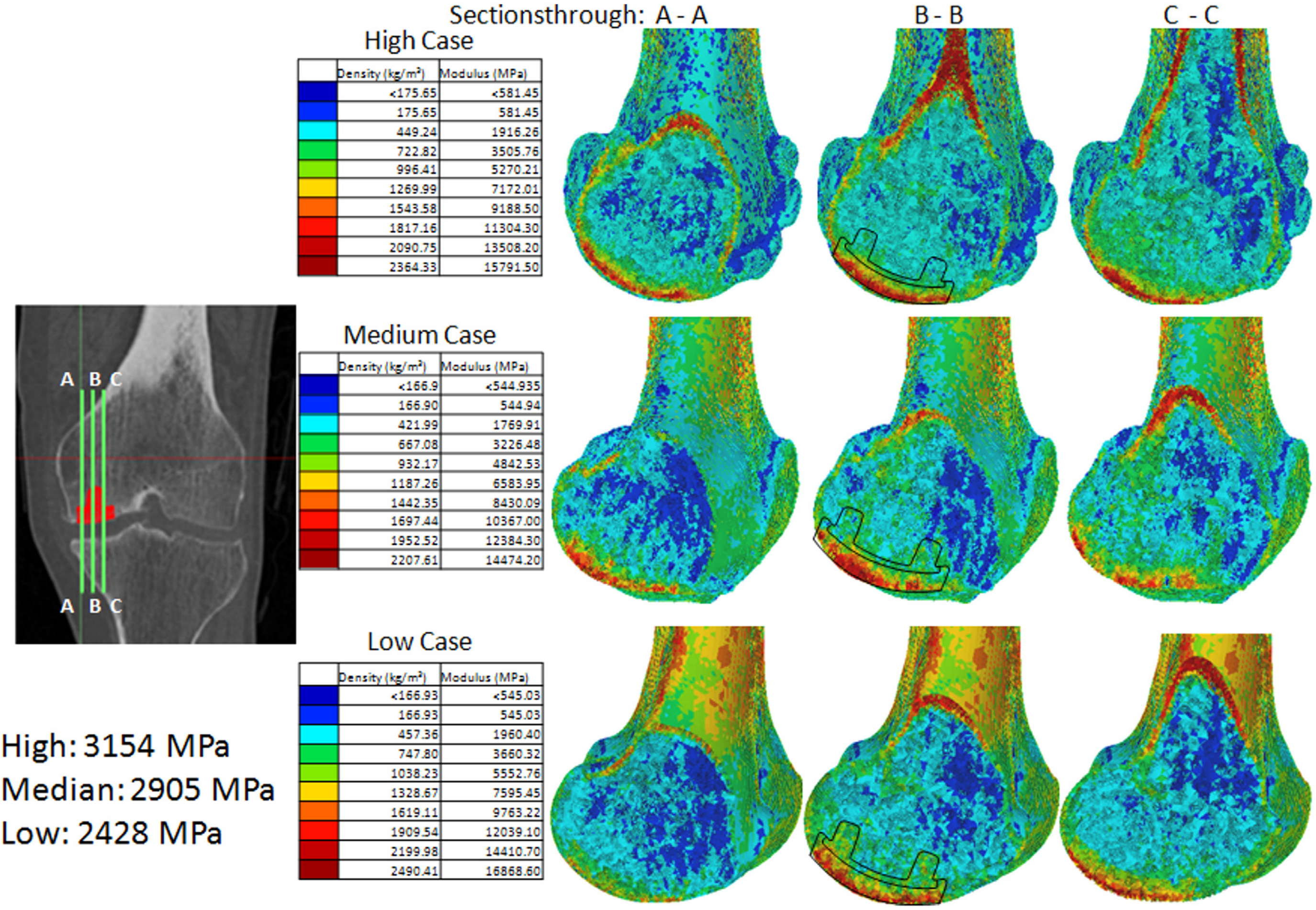
Fig. 1. The two Early Intervention femoral components: metal-backed and all-plastic. The recess for the component is shown, together with the mesh. The metal tibial component is shown also. The sectional diagram (top left) shows the detail of the femoral component inserted in the medial femoral condyle.

Based on our previous analysis of the metal tibial component design, a metal backing may be required for the plastic femoral bearing in order to minimize the stresses and strains at the interface (Chaudhary and Walker, 2014). Clinical experience of all-plastic tibial components showed early failure in many cases due to pain and loosening which can be related to the stress distribution and the weakness of the trabecular support (Gladnick et al., 2015; Saenz et al., 2010).

In this study, our goal was to formulate and analyze a suitable design for the femoral component. The two major design features for consideration was whether a metal-backing would be necessary, as for the tibial component in standard unicompartmental knees, and how the component should be fixed to the bone. The bone density patterns in the medial femoral condyle were a variable that needed to be considered in the analysis. The effect of loading the component at different angles of flexion also needed to be analyzed. The goal was addressed by formulating finite element models of the medial femoral condyle and implant, and subjecting the construct to functional loads.

2. Methods

CT scans taken pre-operatively of 33 patients scheduled for unicompartmental replacements were processed as described previously (Wong et al., 2012). The DICOM files (Siemens, 120 kVp, 1 mm increment) were imported into Mimics 17.0 software (Materialise, Leuven, Belgium), segmented slice-by-slice, and rendered to create a 3-dimensional model of the distal femur. Frontal and horizontal slices were taken and displayed to provide a color-coded visualization of the relative densities between the medial and lateral sides and with depth below the surface. Three of the clinical cases were selected based on the bone density patterns seen in frontal



High Case

	Density (kg/m³)	Modulus (MPa)
🟦	<175.65	<581.45
🟦	175.65	581.45
🟦	449.24	1916.26
🟩	722.82	3505.76
🟩	996.41	5270.21
🟨	1269.99	7172.01
🟧	1543.58	9188.50
🟥	1817.16	11304.30
🟥	2090.75	13508.20
🟥	2364.33	15791.50

Medium Case

	Density (kg/m³)	Modulus (MPa)
🟦	<166.9	<544.935
🟦	166.90	544.94
🟦	421.99	1769.91
🟩	667.08	3226.48
🟩	932.17	4842.53
🟨	1187.26	6583.95
🟧	1442.35	8430.09
🟥	1697.44	10367.00
🟥	1952.52	12384.30
🟥	2207.61	14474.20

Low Case

	Density (kg/m³)	Modulus (MPa)
🟦	<166.93	<545.03
🟦	166.93	545.03
🟦	457.36	1960.40
🟩	747.80	3660.32
🟩	1038.23	5552.76
🟨	1328.67	7595.45
🟧	1619.11	9763.22
🟥	1909.54	12039.10
🟥	2199.98	14410.70
🟥	2490.41	16868.60

Fig. 2. Bone density patterns of the sagittal sections of the medial femoral condyles for the three femurs selected for analysis. The location of the implant is shown on the central sections (B-B).