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An efficient method to capture the impact of total knee replacement on a variety of simulated patient types: A finite element study

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ABSTRACT

Osteoporosis resulting in a reduction in bone stiffness and thinning of the cortex is almost universal in older patients. In this study a novel method to generate computational models of the distal femur which incorporate the effects of ageing and endosteal trabecularisation are presented. Application of this method to pre- and post-knee arthroplasty scenarios is then considered. These computational methods are found to provide a simple yet effective tool for assessing the post-arthroplasty mechanical environment in the knee for different patient types and can help evaluate vulnerability to supracondylar periprosthetic fracture following implantation. Our results show that the stresses in the periprosthetic region increase dramatically with ageing; this is particularly true for higher flexion angles. Stresses in the anterior region of the femoral cortex were also found to increase significantly post-implantation. The most dramatic increases in stresses and strains at these locations were observed in old osteoporotic patients, explaining why this patient group in particular is at greater risk of periprosthetic fractures.

1. Introduction

Ageing and osteoporosis both lead to deterioration in bone quality. Due to medical advances the global population as a whole is ageing. Therefore, consideration of how the change in bone quality influences the mechanical environment of the femur after total knee arthroplasty (TKA) assumes great importance, particularly since the number of operations performed each year continues to increase [1]. In general, TKA is a successful operation with implant survival rates at 10–15 years of greater than 90% [2,3]. However, a number of studies have shown the potential for failure or complication arising post-implantation, leading to an increase in the number of revision surgeries performed [4–6]. These studies have also shown that the incidence of periprosthetic supracondylar fracture increases over time, probably due to a combination of "physiological" and periprosthetic osteoporosis. At the time of revision surgery the quality of bone for fixation is important in terms of the stability of the replacement revision prosthesis and hence its longevity. Areas immediately under the primary implants, particularly behind the anterior flange and posterior condyles of the femur develop significant periprosthetic osteoporosis [7–10]. Bone loss under the implant and stress concentrations around the implant are thought to influence the pattern of periprosthetic femoral fracture [6,8,11].

The use of finite element (FE) models as a tool to investigate complex clinical scenarios and critical cases is becoming more widely accepted. These models provide information which cannot easily be obtained from a lab or clinical research investigation. Studies often use CT based inhomogeneous material properties for the bone [12–14] in which the variation of elastic modulus is estimated from the variation of apparent bone density in the specific femur being considered. Few studies in the literature directly compare the influence of healthy and osteoporotic bone on the femur [15–17] due to this specificity, fewer still have investigated the influence of bone properties following joint arthroplasty on the mechanical environment in the femur e.g. [18,19].

In a study of 163 patients, Bousson et al. [20] employed microradiographs and image analysis techniques to investigate the influence of age and gender on the porosity of three sub-regions (endosteal, mid-cortical and periosteal) from the anterior cortex of the femoral mid-shaft. The authors found that pore size and number increased with increasing age in younger patients (< 60 years). Furthermore, it was observed that pore size and number were proportionally similar in each of the three sub-regions in male specimens, whereas female specimens exhibited significant

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cortical thinning in the endosteal sub-region in particular. Similarly, a more recent study of 688 women and 561 men by Russo et al. [21] indicated that cortical thickness in female specimens of 80 years or greater is approximately 50% of that measured in younger female samples. Age related variations to the bone geometry and porosity at the microscopic [20,22] and macroscopic levels [21] can have considerable impact on its mechanical properties and may have serious implications for fracture risk. The majority of previous research has focused on modeling cases representing a normal patient. It has been well documented that as we age our bones undergo mechanical and structural changes [20–22]. As a result implants designed to suit an average and otherwise healthy patient may induce a very different response in an elderly or pathological patient.

In the present study, FE models of the intact and post-TKA (employing posterior stabilising or PS implant) distal femur were developed. The aim of this study was to determine how incorporation of the effects of ageing (by means of a reduction in bone stiffness) and trabecularisation (modelled through pseudo-thinning) of the cortex, influence the observed mechanics post-implantation.

2. Methods

A three-dimensional virtual reconstruction [23] of the large left fourth generation composite femur (Sawbones; Pacific Research Laboratories, Vashon, Washington, USA), was used for this study (Fig. 1). This geometry was subsequently modified to accept the posterior stabilising (PS) implant, also shown in Fig. 1. Physical implant measurements and surgical theatre templates were used in conjunction with computer aided design software (Autodesk Inventor 2010, Autodesk Inc. San Rafael, California, U.S) to develop 3D models of the femoral implant; the same software was also used to incorporate surgical cuts into the femur for accommodating a posterior stabilizing (PS) implant (Triathlon® series, Stryker®, Newbury, United Kingdom) as shown in Fig. 1. The position of the implant on the bone was verified by an experienced orthopaedic surgeon (the second author). It is important to note that a number of companies supply similar PS implants (e.g. Stryker: Triathlon™ series; DePuy: P.F.C. Sigma™ series; Smith & Nephew: Genesis II™ series) although minor details of the implant's external/internal geometry vary between manufactures. Finite element meshes for the intact and the implanted femurs were created and analysed in Abaqus 6.8.1 (Dassault Systemes, Simulia, Providence, RI, USA).

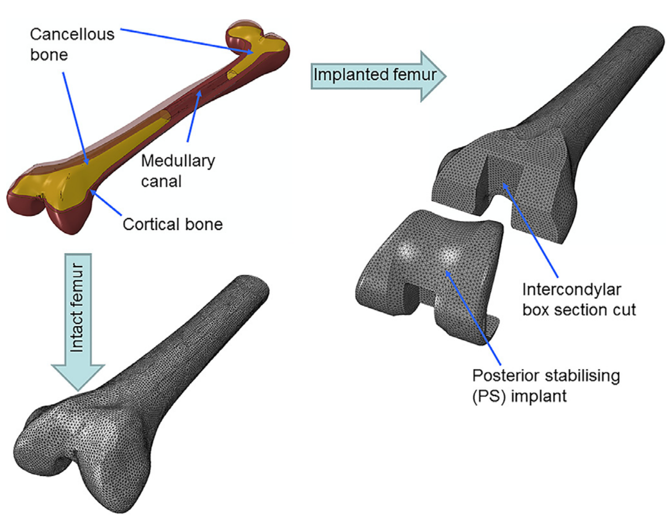

Fig. 1. Creation of intact and PS implanted distal femur FE meshes from CAD model of composite femur.

The meshes typically comprised of 290,000 10-noded tetrahedral elements. The average element size was 2 mm based on convergence studies (a further reduction in element size produced negligible change of displacements/stresses). Simulation runtime for each model was typically in the region of 2-3 hours, on a windows PC with a dual core i5 processor (2.6 GHz) and 8GB of ram.

2.1. Material properties

Cortical bone properties were based on whether healthy or pathological bone was being considered. Previous studies have shown that ageing results in cortical thinning [20,21] and a decrease in bone stiffness [24]. It has also been shown that with ageing, trabecularisation is initiated from the endosteum [20] resulting in the endosteum becoming much less stiff than the periosteum [24].

In this study, a heat transfer analysis was used as an artifice to assign variable elastic properties through the cortical thickness, e.g. from endosteum to periosteum. For this we took advantage of analysis capabilities available in Abaqus 6.8.1 used in this study. Indeed heat transfer capabilities are widely available in several FE packages. The first step was to assign a temperature of $\theta_1 = 0$ to the endosteal surface and a temperature of $\theta_2 = 1$ to the periosteal surface (Fig. 2a). A heat transfer analysis was then conducted with a unit value of thermal conductivity $k = 1\text{W/mm·K}$ and the temperatures were permitted to reach a steady state. The variation of temperatures through the cortical thickness is shown in Fig. 2a and b. These temperatures were then used as a proxy to assign variable elastic moduli to bone as a function of distance through the cortex, as shown in Fig. 2c, to create age dependent models. Before discussing these models it is important to emphasise that the variation of temperature so obtained (not the value itself) will not depend on the initial temperatures chosen (they only need to be different at the two surfaces) or the thermal conductivity. A similar technique was used by Davis et al. [25] to define regional inhomogeneity over complex biological structures.

In the current study, four relationships were then defined between Young's modulus (E) and temperature in order to characterise the inhomogeneity of bone properties (young and old) and to model cortical thinning as shown in Fig. 2c, as can be seen from the Figure, the periosteum always had a higher elastic modulus than the endosteum. Also the elastic moduli at the periosteum for old healthy (OH) and old osteoporotic (OOP) were assumed to be lower (16,700 MPa) than young healthy (YH) and young osteoporotic (YOP) bone (22,000 MPa).

Physically changing the geometry of the femur model to that of an osteoporotic geometry is not a trivial task due to its complex organic shape. Nevertheless, such changes are likely to be of significance to patient outcomes post-implantation. In this study, osteoporotic bone (both young and old) was characterised by a Young's modulus equivalent to that of cancellous bone (155 MPa) at the physical endosteum of the model, while the healthy endosteal value was offset to a spatial position representative of 50% of the cortical thickness (Fig. 2c mid-points on graph) using the aforementioned method for assigning a spatial distribution of properties to the bone. In this manner, the effect of cortical thinning was approximated through manipulation of stiffness values, acting as a proxy for geometrical changes which may occur due to osteoporosis and trabecularisation of the endosteum. Bousson et al. [20] showed that porosity increases more rapidly from periosteum to endosteum for older patients and Donaldson et al. [24] showed that for the femoral cortex porosity is linearly related to Young's modulus. The created models attempt to represent this. The Young's moduli at the endosteum were 16,700 MPa and 7000 MPa for YH and OH cases respectively. Values for both young and old bone material properties were based on values (average of