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The influence of the representation of collagen fibre organisation on the cartilage contact mechanics of the hip joint

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ABSTRACT

The aim of this study was to develop a finite element (FE) hip model with subject-specific geometry and biphasic cartilage properties. Different levels of detail in the representation of fibre reinforcement were considered to evaluate the feasibility to simplify the complex depth-dependent fibre pattern in the native hip joint. A FE model of a cadaveric hip with subject-specific geometry was constructed through micro-computed-tomography (μCT) imaging. The cartilage was assumed to be biphasic and fibre-reinforced with different levels of detail in the fibre representation. Simulations were performed for heel-strike, mid-stance and toe-off during walking and one-leg-stance over 1500 s. It was found that the required level of detail in fibre representation depends on the parameter of interest. The contact stress of the native hip joint could be realistically predicted by simplifying the fibre representation to being orthogonally reinforced across the whole thickness. To predict the fluid pressure, depth-dependent fibre organisation is needed but specific split-line pattern on the surface of cartilage is not necessary. Both depth-dependent and specific surface fibre orientations are required to simulate the strains.

1. Introduction

Finite element (FE) models of the natural hip have the potential to be used to examine how diseases and therapies affect the biomechanical performance of the joint (Henak et al., 2013; Li et al., 2014b). However, there are a number of challenges to the incorporation of the geometrical and material properties with sufficient realism to enable meaningful predictions to be made.

From a geometric perspective, it has been shown that FE models with realistic joint geometry predict different contact mechanics than models with idealised geometry (i.e. spherical joint geometry and uniform cartilage thickness). This is reflected in more irregular distributions of stress and strain and higher magnitudes of contact stress in the more realistic geometry models (Anderson et al., 2010).

From a materials perspective, the biomechanical performance of the joint is closely linked to the biphasic structure of the cartilage (interstitial fluid and solid matrix) as well as to the organisation of collagen fibres embedded within its solid matrix (Mow et al., 1980; Ateshian et al., 1994; Li et al., 2000; Korhonen et al., 2003; Shirazi et al., 2008).

The importance of interstitial fluid within the cartilage to the biomechanical function of the hip joint has been demonstrated in FE models with idealised geometry (Li et al., 2013, 2014a), where the cartilage has been represented as a biphasic material. Here it was found that, for short term and dynamic loading, the interstitial fluid within the cartilage supports the majority of the load through pressurisation and only a small portion of load is supported by the solid matrix.

The collagen fibres within the cartilage provide mechanical stiffness and maintain the structure of the solid matrix (Mow et al., 1980; Ateshian et al., 1994). It has been demonstrated that the inclusion of isotropic fibre reinforcement in the cartilage (i.e. different properties in tension and compression) within FE models of the hip greatly alters the predicted contact mechanics (Li et al., 2014c). Through the thickness of healthy cartilage, fibres are distributed in different patterns. The tissue thickness can be divided into three regions: the surface zone in which fibres are parallel to the articulating surface, the middle zone in which fibres are randomly distributed and the deep zone where fibres are perpendicular to the subchondral bone (Weiss et al., 1968; Mow et al., 1992; Buckwalter et al., 1994). The fibre orientation in the surface zone of cartilage can be visualised by inserting a needle dipped in ink into the surface of cartilage and is sometimes referred to as the split-line pattern. In the healthy hip joint, fibres in the surface zone align towards the fossa of acetabulum and femoral head (Mital and

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Millington, 1970), hypothesised to align with the directions of maximum principal tensile strain (Bullough and Goodfellow, 1968; Armstrong, 1986).

The representation of fibre orientation in the surface zone of cartilage has been demonstrated to play an important role in FE models of the knee as well as at the tissue level (Mononen et al., 2012; Li et al., 2009). However, the effect of the inclusion of more realistic fibre orientation in FE models of the hip has not been previously investigated. One of the main challenges is that the incorporation of zonal differences of fibre pattern into whole joint computational models requires the cartilage to be modelled with a number of elements through the thickness, leading to lengthy pre-processing and processing of the model (Li and Gu, 2011). There is also a need to evaluate the necessity of incorporating the complex depth-dependent fibre pattern in the whole hip joint.

In recent studies, biphasic fibre-reinforced materials have been incorporated into FE models of whole joints (Dabiri and Li, 2013; Halonen et al., 2014; Mattei et al., 2013). However, to achieve numerical convergence, these models were either only loaded to a low level of load (non-physiological) (Mattei et al., 2013; Dabiri and Li, 2013; Halonen et al., 2014) or monophasic materials were used as one of the bearing surfaces (e.g. biphasic cartilage in contact with elastic meniscus in the knee (Mononen et al., 2012; Kłodowski et al., 2015) and hemiarthroplasty in the hip (Pawaskar et al., 2010, 2011)).

Recently, using an open source FE solver specifically designed for biomechanical applications (FEBio, http://febio.org/febio), convergence has been improved in a hip FE model with idealised geometry, enabling physiological loads to be applied (Li et al., 2013, 2014a). In a recent study, this method has also been used to simulate a porcine hip hemiarthroplasty model in which both biphasic cartilage and realistic joint geometry were considered (Li et al., 2014c). However, biphasic fibre-reinforced properties have yet to be incorporated into 3D whole hip models with subject-specific geometry under physiological loading.

The aim of this study was to evaluate the effect of implementing different levels of detail in the fibre reinforcement within the articular cartilage of a hip FE model. Specifically, the objectives were to examine the need for realistic split-line representation of fibre orientation in the surface layer, and for implementing different fibre patterns through the cartilage thickness. To this end, a FE model of the hip with subject-specific geometry incorporating biphasic fibre-reinforced cartilage properties that could be solved under both physiological and prolonged loading was developed. The effect of the different levels of detail in the fibre representation was examined in terms of differences in the predicted contact mechanics and cartilage strain states.

2. Methods

2.1. Imaging, segmentation and solid model construction

A femur and a pelvis from a 55 year-old 109 kg male at the time of death (cause of death: alcoholic cirrhosis of the liver) was adopted in this study. Non-transplantable human cadaveric tissue was supplied by Platinum Training and its use approved by the University of Leeds research ethics committee. The position of femur and pelvis were recorded based on anatomical landmarks (Bergmann et al., 2001). The specimen was then dissected to retain the hip region. A subject-specific FE model of this hip specimen was constructed and simulated using a validated process described previously (Li et al., 2014c). Briefly, the femoral and acetabular components were imaged separately using a micro-computed-tomography (μCT) scanner (μCT 80, SCANCO Medical AG, Brüttisellen, Switzerland) at a cubic voxel size of 73.6 μm and energy of 70 kVp, 114 μA, providing good visualisation of the bone and cartilage. The volumetric μCT data were segmented and smoothed in an image processing software package (ScanIP version 5.1; Simpleware Ltd., Exeter UK) and then exported into Geomagic Studio (version 11, Geomagic Inc., Research Triangle Park, NC, USA) to construct the solid model (Fig. 1a) which was meshed in ABAQUS (version 6.11-1, Dassault Systemes, Suresnes Cedex, France) (Fig. 1b).

2.2. FE model construction and material properties

To facilitate the incorporation of the pattern of collagen fibres in the surface zone (i.e. aligned towards the fossa of the acetabulum and femoral head (Mital and Millington, 1970) (Fig. 1a)), the solid model of the cartilage was partitioned along the split-lines so that the meshed elements and fibres could be oriented along these directions (Maas et al., 2012). The model was meshed with six layers of elements through the cartilage thickness. It has been reported that in healthy cartilage, the surface, middle and deep zones account for 10–20%, 40–60% and 30–40% of the thickness (Mow et al., 1992, Buckwalter et al., 1994), and were therefore represented by one, three and two layers of elements respectively

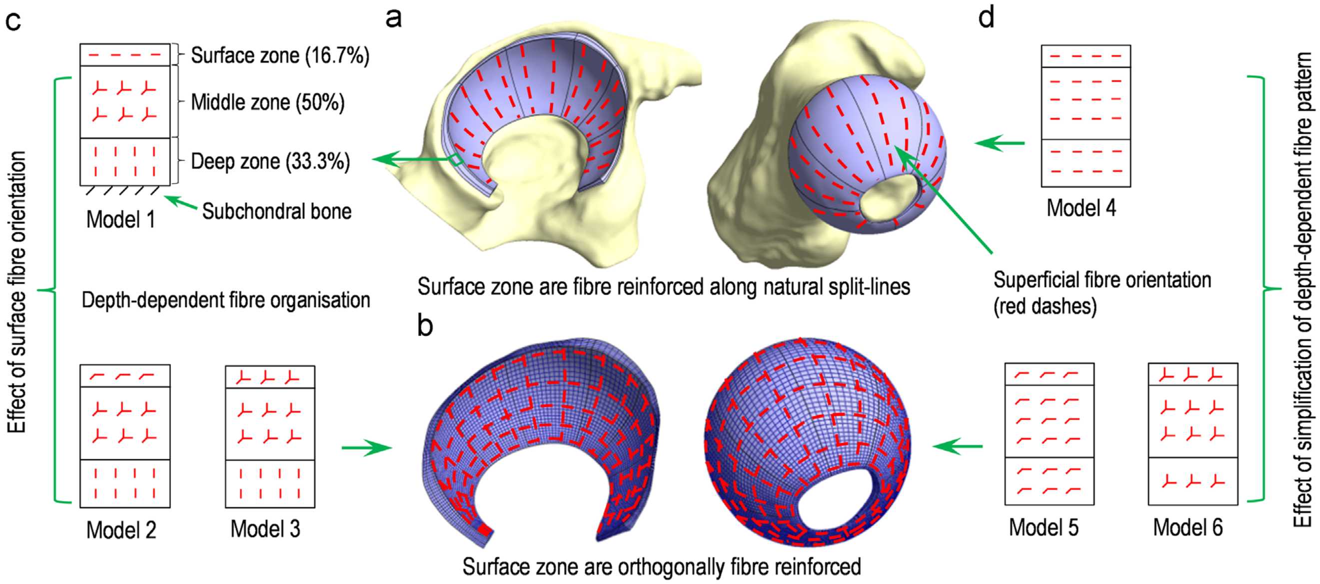

Fig. 1. Creation of FE models with different fibre patterns. Models 1, 2 and 3 had depth-dependent fibre reinforcement pattern (c). Fibres were assumed uniformly distributed in all directions in the middle zone and perpendicular to the subchondral bones surface in the deep zone. Fibre reinforcement in the surface zone of Models 1, 2 and 3 had different orientations: along a single direction following the natural split-line pattern in Model 1; orthogonally across the articulating surfaces in Model 2; uniformly distributed in all spatial directions in Model 3. Models 4, 5 and 6 had a uniform fibre pattern through the thickness (d) with all the fibres oriented in a single direction following the natural split-line pattern in Model 4; orthogonal fibre distribution parallel to the articulating surfaces in Model 5 and uniform fibre distribution in all spatial directions in Model 6.

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