INTRODUCTION
Radial head fractures are the most common fractures occurring in about 30% of the fractures involving the elbow joints [1, 2]. Fractures of the radial head and neck are usually the result of a fall on the outstretched arm with the impact force transmitted up the hand through the wrist and forearm to the radial head [3]. Radial head fractures are classified as three types (Type I, II, and III) by Mason according to the degree of displacement and the extent of fractures; several modified classification systems, such as Broberg-Morrey modification [4], have been developed since. Radial head replacement is conducted for displaced radial head fractures with more than 3 fracture fragments (Type III) when ORIF (Open Reduction and Internal Fixation) is not advisable [5]. Various implants are available in the market and current popular prostheses are manufactured from cobalt-chrome alloys. The purpose of this study is to develop a finite element model for the elbow including soft tissue constraints to evaluate various radial head implants with different shapes and materials.

METHODS
A finite element model for the elbow joint was constructed from computed tomography of a cadaver elbow. Figure 1 represents the 3-D solid bone model and FE model for the elbow joint extracted from CT scans using Mimics medical imaging software (Materialise, Leuven, Belgium) and Geomagic studio (Geomagic inc., Triangle Park, NC). The elbow was modeled in the neutral supination/pronation position. The elbow was flexed at 27°. The FE model included cartilage, annular ligament and radial collateral ligament. Cartilage was added on all three bones only where contacts could occur and was assumed to have a uniform thickness of 1.0 mm. Three stiff spring elements were used for the ligaments and 59,371 ten-node tetrahedral elements were used for bones and cartilage. For the contact analysis contact and target elements were added on each cartilaginous surface. Cartilage and ligaments were modeled as isotropic materials whereas bones were modeled as transversely isotropic. All three bones were assumed to be cortical bone. Material properties of bone, cartilage and ligament are listed in Table 1. The proximal ends of the humerus and ulna were constrained in all directions and an axial load of 2 MPa on the distal surface of the radial head, which is equivalent to 588 N, was applied, directed-toward the humerus. The finite element package, ANSYS (ANSYS Inc., Canonsburg, PA), was used for the calculations of contact stresses in two contact regions (the radial head and capitellum; and the radial head and ulnar notch). The normal pressure applied to the radial head and the capitellum was computed as the average over all elements that used the node with the single highest value.

![Fig. 1 3D solid model and FE model for the elbow joint](image)

<table>
<thead>
<tr>
<th>Part</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>$E_h = E_r = 7.0; E_i = 11.5, G_{hy} = 2.6; G_{hr} = 2; G_{ry} = 3.5$</td>
<td>0.4</td>
</tr>
<tr>
<td>Cartilage</td>
<td>0.012</td>
<td>0.35</td>
</tr>
<tr>
<td>Ligament</td>
<td>2</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 1 Material properties [6, 7]

RESULTS
Contact stress distributions of the radial head and capitellum are shown in Figure 2. The averaging over elements produced different contact stresses on the capitellum and radial head. The maximum normal contact stress of cartilage on the radial head was 9.34 MPa whereas that on the capitellum was 7.12 MPa. This maximum stress was located antero-laterally from the center of the radial head. For axial loading, the contact stress between the radial head and the ulnar notch was essentially zero. Although the maximum contact stresses of the radial head and the capitellum were not identical, the contact areas on the head and the capitellum were the same.

![Fig. 2 Contact stresses of the radial head (left) and the capitellum (right)](image)

DISCUSSION
The concentration of the normal contact stress of the radial head in the antero-lateral region, concurs with the findings of Takatori et al. [8] and Inoue et al. [9]. Takatori et al. used pressure sensitive film, a tactile sensor and finite element analysis to quantify the stress distribution of the humeroradial joint, finding that stress concentration occurred on the lateral side in supination. Inoue et al. used pressure sensitive film and radiographic analyses and reported that stress was concentrated in the anterolateral region of the radial head in supination.

The inclusion of ligaments and ununohumeral cartilage in the current model extend the physiological characteristics beyond previous work. Compared to the results of Takatori et al., because the contact stress between the radial head and the ulnar notch as well as that between the radial head and the capitellum were calculated, the FE model in this study was designed to fully evaluate different radial head implants for additional load cases. Although the radial head and capitellar contact stress are expected to differ slightly in a computational model, the discrepancy between the radial head and capitellar normal stresses is due in part to the averaging method which meant different patches of area on the surfaces were used in the calculation. A convergence study provided confidence that the results were correct, but further smoothing of the surfaces with a remeshing should be performed. In addition to the axial loading, future study will include large forces in the pronator teres, which cause axial and transverse loading.

REFERENCES