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A patient-specific model of total knee arthroplasty to estimate patellar strain: A case study

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ABSTRACT

Background: Inappropriate patellar cut during total knee arthroplasty can lead to patellar complications due to increased bone strain. In this study, we evaluated patellar bone strain of a patient who had a deeper patellar cut than the recommended.
Methods: A patient-specific model based on patient preoperative data was created. The model was decoupled into two levels: knee and patella. The knee model predicted kinematics and forces on the patella during squat movement. The patella model used these values to predict bone strain after total knee arthroplasty. Mechanical properties of the patellar bone were identified with micro-finite element modeling testing of cadaveric samples. The model was validated with a robotic knee simulator and postoperative X-rays. For this patient, we compared the deeper patellar cut depth to the recommended one, and evaluated patellar bone volume with octahedral shear strain above 1%.
Findings: Model predictions were consistent with experimental measurements of the robotic knee simulator and postoperative X-rays. Compared to the recommended cut, the deeper cut increased the critical strain bone volume, but by less than 3% of total patellar volume.
Interpretation: We thus conclude that the predicted increase in patellar strain should be within an acceptable range, since this patient had no complaints 8 months after surgery. This validated patient-specific model will later be used to address other questions on groups of patients, to eventually improve surgical planning and outcome of total knee arthroplasty.

1. Introduction

Despite relatively high success rate of total knee arthroplasty (TKA), 11% to 19% of primary TKA patients are not satisfied with the surgical outcome and around 6% of patients go for a revision surgery due to postoperative complications (Bourne et al., 2010; Bozic et al., 2010; Pabinger et al., 2013; Von Keudell et al., 2014). Among those, up to 24% of the revision surgeries can be caused by complications related to the patella: osteonecrosis, patellar fracture, implant failure, polyethylene wear, extensor mechanism rupture, and anterior knee pain (AKP) (Bozic et al., 2010; Schindler, 2012; Sundberg et al., 2014).

In vivo (Carpenter et al., 2009; Sharma et al., 2012), *in vitro* (Lie et al., 2005; Matsuda et al., 1997; Merican et al., 2014) and *in silico* (Amirouche et al., 2013; Fitzpatrick et al., 2011; Takahashi et al., 2012) studies have shown that TKA leads to significant changes in patellar kinematics, forces acting on the patella, and resulting bone strain in comparison with the intact knee. One of the possible causes of these changes can be related to a surgical technique influencing the positioning of the prosthetic components, their rotation around the joint axes, and the amount of bone cut. Even though surgical techniques have been improved during the last decades, and navigational systems as well as patient-specific cutting guides make the surgery more controllable (Franceschi and Sbihi, 2014), patellar resurfacing still remains the less controllable part of the procedure. Small size of the patellar bone, surrounding soft tissues and osteophytes, difficulty of finding anatomical landmarks, and thickness of the cutting jigs can easily lead to deeper bone cut or unwanted resection angles (Anglin et al., 2009).

Several numerical and *in vitro* studies showed that reduction of patellar thickness can lead to increase of patellar bone strain (Amirouche et al., 2013; Fitzpatrick et al., 2013; Lie et al., 2005), thus increasing risk of the patellar fracture and possibly contributing to AKP symptoms (Draper et al., 2012; Ho et al., 2014). However, these studies were conducted on cadaveric knees. To the best of our knowledge, no studies tried to estimate patellar bone strain and effect of bone resection on

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real TKA patients. The estimation of the strain in TKA patients could help to evaluate strain ranges that should be kept after surgery in order to avoid complications. Such knowledge in combination with a patient-specific numerical model would help to improve patellar resection technique during surgery planning. Moreover, all numerical models predicting patellar bone strain assign elastic properties measured on other bones than the patella (Fitzpatrick et al., 2011; Ho et al., 2014; Takahashi et al., 2012) due to the limited number of studies focused on the measuring of patellar mechanical properties.

Hypothesizing that an inappropriate patellar cut increases the risk of postoperative patellar complications, and that numerical model could help to estimate this risk through prediction of patellar bone strain, in the present study we investigated the retrospective case of a TKA patient who had a resection of the patellar bone that was deeper than usually recommended. The first objective was to develop and validate a patient-specific TKA model replicating squat movement. This model should be able to predict postoperative patellar strain using patient preoperative data, such as CT scan, height, weight, implant design, and preoperative planning. Our second objective was to use this model to analyze the influence of the patellar cut depth on patellar strain.

2. Methods

A patient-specific TKA numerical model was developed from preoperative data of a TKA patient. A loaded squat movement was simulated. The TKA model was decoupled into two levels: knee and patella. The knee model predicted kinematics and forces on the patella. The patella model used these values to predict bone strain. For this patient, we compared the effect of the patellar cut depth on patellar kinematics and strain.

2.1. TKA patient

The TKA patient chosen for this study was a 78-year-old female (156 cm, 68 kg). A specific TKA preoperative CT protocol was designed to obtain the 3D volume-rendered reconstructions of the knee joint and thigh muscles, and to estimate the centers of the hip and ankle joints (Fig. 1a). CT data were acquired on a multidetector CT scanner (Discovery CT750 HD, GE Healthcare, Milwaukee, USA). The standard CT protocol was extended by adding a set of eighteen 1.25-mm-thick slices evenly distributed along thigh muscles from the acetabular roof to femoral condyles (Narici et al., 1992). The patient received a cemented ultra-congruent posterior-stabilized mobile-bearing knee prosthesis (F.I.R.S.T.; Symbios, Yverdon-les-Bain, Switzerland) with a three-peg modified dome patellar component. Patient-specific cutting guides were used to insert the femoral and tibial components (Franceschi and Sbihi, 2014). The patient was followed-up 8 months after surgery. The postoperative X-rays revealed a 12 mm patellar cut depth instead of the recommended 9 mm corresponding to the thickness of the patellar component (Fig. 2).

2.2. Knee model

The knee model included the femur, tibia, patella, quadriceps and hamstring (Fig. 1c). We considered the four quadriceps muscles: rectus femoris (RF), vastus intermedius (VI), vastus lateralis (VL), vastus medialis (VM); and the three hamstring muscles: biceps femoris (BF), semitendinosus (ST), and semimembranosus (SM). Bone and muscle geometry was reconstructed by segmentation of CT images (Amira; FEI Visualization Sciences Group, Burlington, USA) (Fig. 1b). In case of muscle reconstruction, the segmentation was interpolated between eighteen slices. The prosthesis was positioned into the model according to preoperative planning, and verified with postoperative X-ray. Patellar cut was estimated from postoperative X-ray (lateral and sunrise view).

We implemented the knee model in Abaqus (Simulia, Providence, USA). Bones and metallic components were rigid. Polyethylene tibial insert and patellar button were linear elastic ($E = 572$ MPa, $\nu = 0.45$) (Fitzpatrick et al., 2011). Patellar tendon was modeled by two nonlinear springs (Staubli et al., 1996, preconditioned state). Medial and lateral patellofemoral ligaments were modeled by two linear fibers each with 10% pre-strain (Atkinson et al., 2000; Marra et al., 2015; Merican et al., 2009). Quadriceps tendons were linear fibers ($E = 1.2$ GPa, Cross Sectional Area $= 62.5$ mm^2) (Voigt et al., 1995) and could wrap around femoral surface at deep angles of flexion. The seven muscles were represented by seven pair of nodes defining muscle lines of action. Directions of four quadriceps muscles in frontal plane were taken from literature (Sakai et al., 1996, anatomical model), while to define position in sagittal plane the lines were directed through the muscle origins on

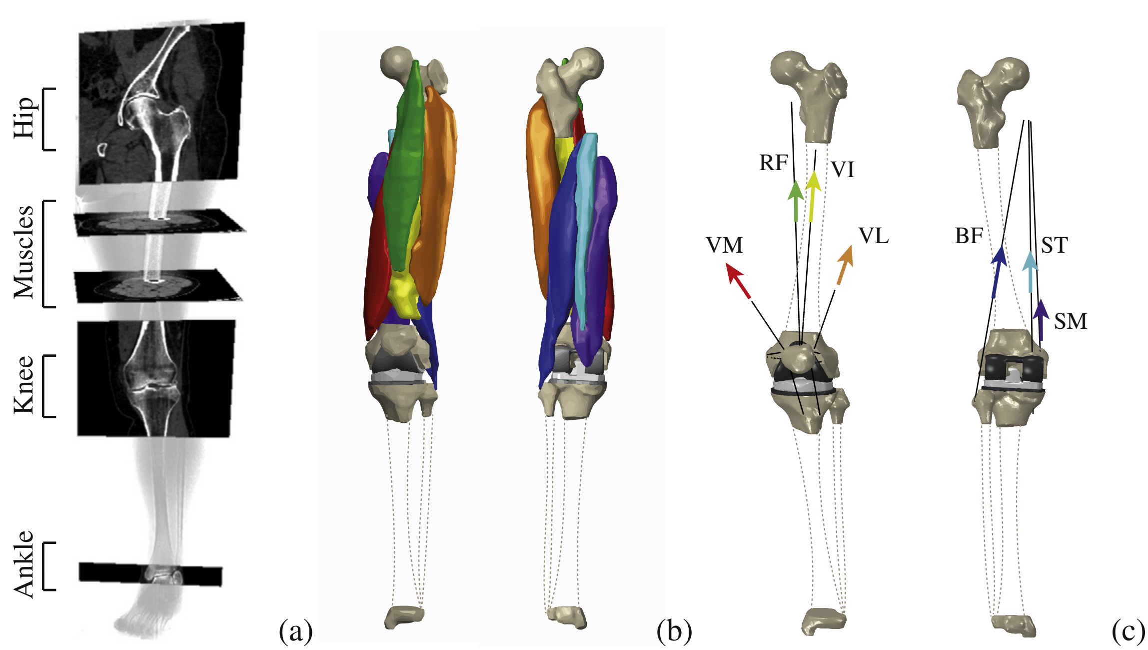

Fig. 1. Patient preoperative CT dataset: hip, knee, and ankle joints, and thigh muscles (a); anterior and posterior views of 3D volume-rendered reconstruction of bones, muscles, and prosthesis (b); and anterior and posterior views of the knee joint model (c).